Volume 25 DECEMBER, 1955 Number 4

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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The subscription price of the *Journal of Sedimentary Petrology* is $6.00 per year prepaid to addresses in the United States.

Single numbers, $2.00 each ($1.50 to members).

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $6.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about *Journal* subscriptions, rates, memberships, change of address, and non-receipt of preceding number should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

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Annual Membership dues, including the Journal of Sedimentary Petrology .. 5.00
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GEORGE BANTA COMPANY, INC., MENASHA, WISCONSIN
PRINTED IN THE U.S.A.

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal,* should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Mottled carbonate rocks in the middle Devonian of eastern Nevada. By John C. Osmond

A simple turbidimeter. By John S. Bradley

A manual piston coring device for use in shallow water. By Robert N. Ginsburg and R. Michael Lloyd

Clay minerals from the Röt member of the Triassic near Göttingen (Germany). By Friedrich Lippman

A hand auger for boring recent sediments. By James P. Morgan and William G. McIntire

Lower limits to the *So* coefficient. By William F. Tanner

A new method of expressing particle sphericity. By Bert C. Aschenbrenner

Soil boulders in the Temecula arkose. By John F. Mann, Jr.

Origin of calcareous ooliths. By P. H. Monaghan and Melba L. Lytle

Graphic aids in study of strata. By Sherman A. Wengerd

Petrology of the arenaceous beds in the Conococheague formation (late Cambrian) in the northern Appalachian valley of Virginia. By Richard L. Nicholas

A use of roundness to determine depositional environments. By M. Allan Beal and Francis P. Shepard.

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FIGS. 1–3, PLS. 1–2, DECEMBER, 1955

PETROGRAPHY OF THE LATE TERTIARY VOLCANIC ASH FALLS IN THE CENTRAL GREAT PLAINS[1]

ADA SWINEFORD, JOHN C. FRYE, AND A. BYRON LEONARD
State Geological Survey of Kansas, Illinois State Geological Survey, and University of Kansas

ABSTRACT

Lenticular deposits of volcanic ash in the Miocene and Pliocene strata of western Kansas and western Nebraska are described petrographically. These include 14 ash falls of known stratigraphic position. All the ash studied is classed as vitric tuff and most of the falls are rhyolitic in composition. A regular or progressive change through time in the character of the ash does not occur. Ash falls are particularly common in the lower half of the Ash Hollow member of the Ogallala formation where it is estimated that volcanic material constitutes more than three percent of the volume of the sediments.

INTRODUCTION

The presence of discontinuous local lentils of volcanic ash within the late Tertiary deposits of the central Great Plains has been known since the early geologic reconnaissance surveys, and some deposits have been mined commercially for more than half a century. In 1946 Swineford and Frye compared petrographically a few deposits of Ogallala volcanic ash in northern Kansas with the Pleistocene Pearlette ash, but heretofore no systematic petrographic study of the ash falls of Miocene and Pliocene age in this region has been made.

Interest in volcanic ash petrography has been stimulated in recent years by the use of distinctive petrographic characteristics of a single ash fall as an aid to stratigraphic correlation (Frye, Swineford, and Leonard, 1948). The present investigation was carried out in support of a stratigraphic study of the Ogallala formation in the course of which all known ash deposits of the Ogallala in Kansas and the ash in the type localities of named stratigraphic units in late Tertiary deposits in central and western Nebraska were examined and sampled. Furthermore, to avoid the possibility of confusing Ogallala ash with older ash deposits of the Plains region, volcanic ash at known stratigraphic positions within the Miocene deposits of western Nebraska was studied and sampled. As a result, 13 volcanic ash falls of known or determinable stratigraphic position (fig. 1) and several additional ash lentils of uncertain stratigraphic position within the Ash Hollow member of the Ogallala formation were studied.

It is the purpose of this paper to describe the petrographic characters of these ash beds of the central Great Plains region.

We express our thanks to E. C. Reed, State Geologist of Nebraska, for courtesies extended during the course of our work.

LATE TERTIARY VOLCANIC ASH FALLS

Late Tertiary ash beds described here range in age from lower Miocene (Lugn, 1939; Schultz and Stout, 1941) to middle Pliocene. The Miocene ash falls are represented by one or two localities each in the Gering and Harrison formations of the Arikaree group (Lugn, 1939) and the Spottedtail, Sand Canyon, and Box Butte members of the Sheep Creek formation (Elias, 1942) of the Hemingford group. All Miocene ash localities described occur in central and western

[1] Published by permission of the Director, State Geological Survey of Kansas.

SERIES	GROUP	FORMATION	MEMBER	VOLCANIC ASH BED
Pliocene		Ogallala	Kimball	
			Ash Hollow	Reamsville Reager *[Unnamed ash* Dellvale *lentils from* Ft. Wallace *Nebr. and Kans.]* Rawlins
			Valentine	Calvert *Unnamed lower ash*
Miocene	Hemingford	Sheep Creek	Box Butte	*Box Butte ash*
			Sand Canyon	*Upper Sand Canyon ash* *Lower Sand Canyon ash*
			Spottedtail	*Spottedtail ash*
		Marsland		
	Arikaree	Harrison		*Harrison ash*
		Monroe Creek		
		Gering		*Gering ash*

FIG. 1.—Chart showing stratigraphic succession of described late Tertiary volcanic ash falls in the central Great Plains.

Nebraska (fig. 2). The Pliocene ash falls are generally represented by a relatively large number of localities; six have been assigned formal names (fig. 1). Of these only the Calvert bed occurs in the lower Pliocene Valentine member of the Ogallala formation. The Rawlins, Fort Wallace, Dellvale, Reager, and Reamsville beds and six unnamed local lentils are within the middle Pliocene Ash Hollow member of the Ogallala formation. No volcanic ash was studied from the Kimball, uppermost member of the Ogallala formation.

General Petrography

All the late Tertiary volcanic ash deposits studied by us are predominantly vitric tuffs. A few deposits contain traces of volcanic quartz, sanidine, and biotite, and two or three lentils are characterized by large quantities (two to five percent) of biotite.

Except for the deposits rich in biotite, the ash falls are differentiated entirely by the character of the glass shards, including average value and range of index of refraction; thickness, shape, and color of shards; presence or absence of small second-order vesicles in the glass; and chemical composition of the glass. Most of these characters—notably refractive index, color, and chemical composition—are affected to some extent by the degree of alteration or weathering of the glass and must be evaluated with caution.

The index of refraction of the fresh glass in all except one sample is between 1.493 and 1.515. The one exception contains shards having an index as high as 1.564.

Some ash falls are characterized by shards which are simple and so thin that iridescence is observed in a few fragments. Other falls contain coarse glass

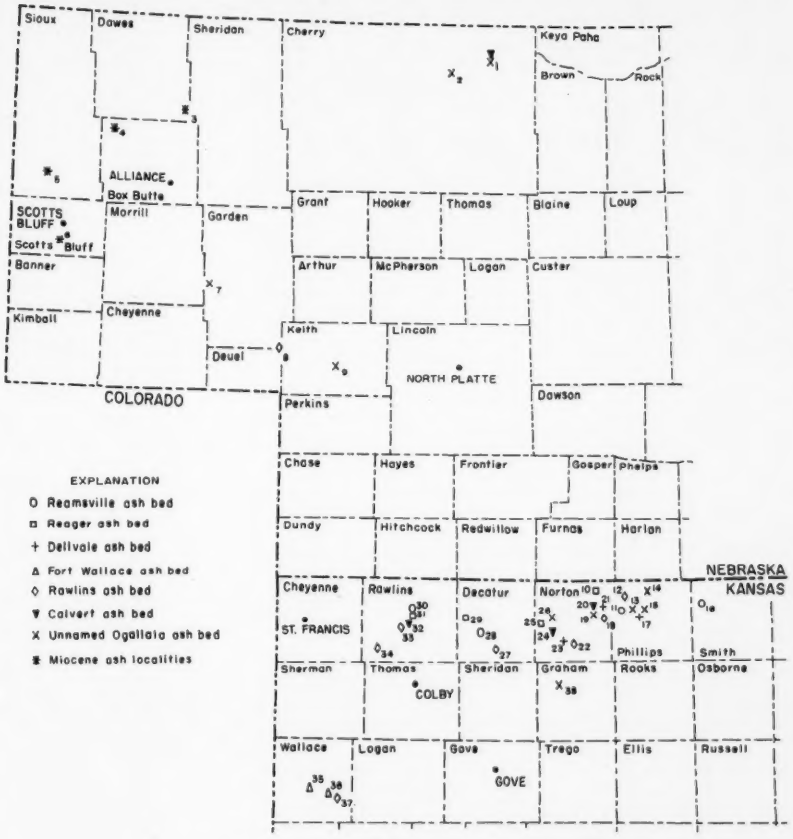

FIG. 2.—Map showing location of volcanic ash lentils studied in western Kansas and western Nebraska.

shards 20 microns thick or thicker. Glass in some deposits has a small radius of curvature of the bubble walls, a frothy to fibrous aspect caused by numerous bubbles, or multiple bubble junctures in one shard. Evaluation of shard shape and thickness has not been quantified but is done simply by visual comparison of two or more samples at a time. The data are summarized in table 1.

The chemical composition of most of the samples analyzed is typically high in silica, or approximately that of rhyolite. Discussion of the chemical analyses is deferred to a later section.

Gering Formation

A sample of volcanic ash was collected from the Gering formation in the cuts along the road leading up Scotts Bluff National Monument, Nebraska (Wenzel, Cady, and Waite, 1946) (loc. 6, fig. 2). Here, a 1½-inch bed of volcanic ash occurs in the lower part of the formation four feet below a prominent 18-inch white calcareous mudstone bed.

TABLE 1.—*Optical character of ash falls*

Ash fall	Characteristic index of refraction	Shard shape	Second-order vesicles	Remarks
ASH HOLLOW				
Reamsville	1.497–1.502 ±0.002	Various; some fibrous. Characteristically complex with many junctures.	Common	
Reager	1.502–1.503 ± .002	Thickness variable. Shards moderately simple with a few long parallel junctures and some high-angle junctures.	Rare to absent	Trace biotite.
Dellvale	1.500–1.501 ± .002	Very thin. Common straight parallel junctures.	None	
Fort Wallace	1.507–1.515 Most 1.511 ± .002	Various; thin to thick. Most junctures straight; some coarsely fibrous shards.	Groups of vesicles common	Several percent biotite; trace sanidine. Dark color, owing to biotite.
Rawlins	1.502–1.503 ± .002	Rather thin, with common straight and parallel junctures. Many shards have large circular holes.	None	Basal 2 inches has thicker glass with n=1.503–1.506 ± .002.
Unnamed (Loc. 14, 15)	1.497–1.502 ± .002	Various; some fibrous. Characteristically complex with many junctures.	Common	Except for its slightly greater thickness, similar to Reamsville.
Unnamed (Loc. 13, 19)	1.501 ± .003	Thin, fairly flat, simple. Junctures few and straight.	None	
Unnamed (Loc. 26)	1.504–1.507 ± .002	Moderately thin. Straight parallel and high-angle junctures.	Few or none	
Unnamed (Loc. 7)	N.D.	Thick glass. Many and complex junctures.	All types, common	Trace biobite. Glass slightly altered.
Unnamed (Loc. 9)	1.500–1.504 ± .002	Mostly thin. Straight, closely spaced parallel junctures common.	A few long vesicles	
Unnamed (Loc. 2)	1.502 ± .002	Thick, rather simple. Multiple straight junctures common in coarse shards.	None	
ASH HOLLOW?				
Unnamed (Loc. 38)	1.501–1.510 Most 1.504 ± .002	Various; no fibrous.	Very few	Few percent biotite; trace sanidine. Much devitrified glass.
VALENTINE				
Calvert	1.501 ± .002	Thin, flat, simple. Few junctures.	None	Trace volcanic quartz.
Unnamed (Loc. 1)	N.D.	Simple, rather thick.	None	Trace biotite.
MIOCENE				
(Box Butte)	1.501 ± .003	Thick to thin. Junctures fairly common.	Rare	
(Upper Sand Canyon)	1.506–1.564	Thin to thick; simple to complex.	Common	Salt-and-pepper appearance, owing to scattered dark-brown glass shards.
(Lower Sand Canyon)	1.504–1.511 Most 1.505–1.508	Thick, substantial shards; some coarse fibrous.	Some large vesicles	Color darker than average.
(Spottedtail)	1.503 ± .003	Moderately thick, with many complex small-scale, high-angle junctures. Fibrous shards common.	Very common	
(Harrison)	1.493–1.497 ± .002 (?)	Thick, complex.	Common	Glass visibly porous.
(Gering)	1.499–1.503 ± .002	Thick, complex, frothy, and fibrous. Small radius of curvature.	Very common	Trace sanidine enclosed in glass. Trace biotite.

The glass, which is seemingly nearly fresh, has a refractive index of 1.499 to $1.503 \pm .002$. Most of the shards have an index of about 1.500. The shards are characteristically thick and complex (pl. 1, E); many are fibrous or frothy and contain numerous vesicles. A few grains of sanidine are enclosed in the thick glass. The color of the fraction finer than 62 microns is 10YR 8/2 (Munsell designation). The Gering ash bed does not have the sparkling megascopic appearance of fresh volcanic glass. This may be in part attributable to the small radius of curvature and frothy character of the shards.

Chemical analysis of a sample of this ash (table 2) shows that it is comparatively low in silica (69.09 percent SiO_2) and high in Al_2O_3, TiO_2, and MgO. It is low in K_2O and high in Na_2O compared with other volcanic ash samples analyzed. Adsorbed or included water (loss at 105° C. = 2.61 percent) is much greater than that in most other samples, which lost less than 0.5 percent at 105° C.

Harrison Formation

One sample of volcanic ash was collected from the Harrison formation (Cook and Cook, 1933; Schultz, 1938, 1941; Lugn, 1939; Elias, 1942) where four feet of ash is exposed below the base of the type section of the Sheep Creek formation in Sioux County, Nebraska (loc. 5, fig. 2). The ash, which is partly indurated, occurs about 10 feet below a pipy concretionary zone that marks the local top of the Harrison formation.

The glass of the Harrison ash bed is thick (pl. 1, C) and porous; it is characterized by numerous extremely minute bubbles or vesicles between smooth surfaces. The refractive index seemingly is about 1.493 to $1.497 \pm .002$, but its apparent value may be lowered by the small bubbles. The fraction finer than 62 microns is slightly paler than 5YR 8/1.

Chemical analysis indicates that the Harrison ash bed is slightly lower in silica than most of the deposits studied, and slightly higher in alumina. The TiO_2 content is exceptionally low, but the percentage of MgO (2.09 percent) is the highest of any sample analyzed. The sample also contains more than a trace (0.02 percent) of P_2O_5.

Sheep Creek Formation

In recent Nebraska classification the Sheep Creek formation, named by Matthew and Cook (1909), includes three members: the Spottedtail, Sand Canyon, and Box Butte (Elias, 1942). Each of these members contains volcanic ash and the Sand Canyon member is known to contain two beds.

Spottedtail Member.—At the type locality of the Spottedtail member (Matthew, 1924; Schultz, 1938) (type locality of Sheep Creek formation, sec. 30, T. 26 N., R. 55 W., Sioux County, Nebraska, loc. 5, fig. 2) a six-inch bed of impure, partly cemented volcanic ash was examined. The ash occurs in the approximate middle of a 40-foot interval of massive, very fine sand. The volcanic ash is approximately 100 feet above the unconformable contact of Sheep Creek formation on Harrison formation.

The glass of the Spottedtail volcanic ash bed is characterized by numerous vesicles and complex, small-scale, high-angle bubble junctures. Fibrous shards are common (pl. 1, D). The glass is only moderately thick, and the fraction finer than 62 microns is slightly paler than 5YR 8/1. There is no evidence of alteration in the samples studied. The refractive index is $1.503 \pm .003$.

In chemical composition this ash is somewhat lower in silica and higher in alumina than the average sample analyzed, and it contains 0.09 percent P_2O_5. It is low in TiO_2 but not otherwise unusual.

Sand Canyon Member.—The Sand Canyon member of the Sheep Creek formation was named and described by Elias in 1942. Several localities of volcanic ash are known to occur at two

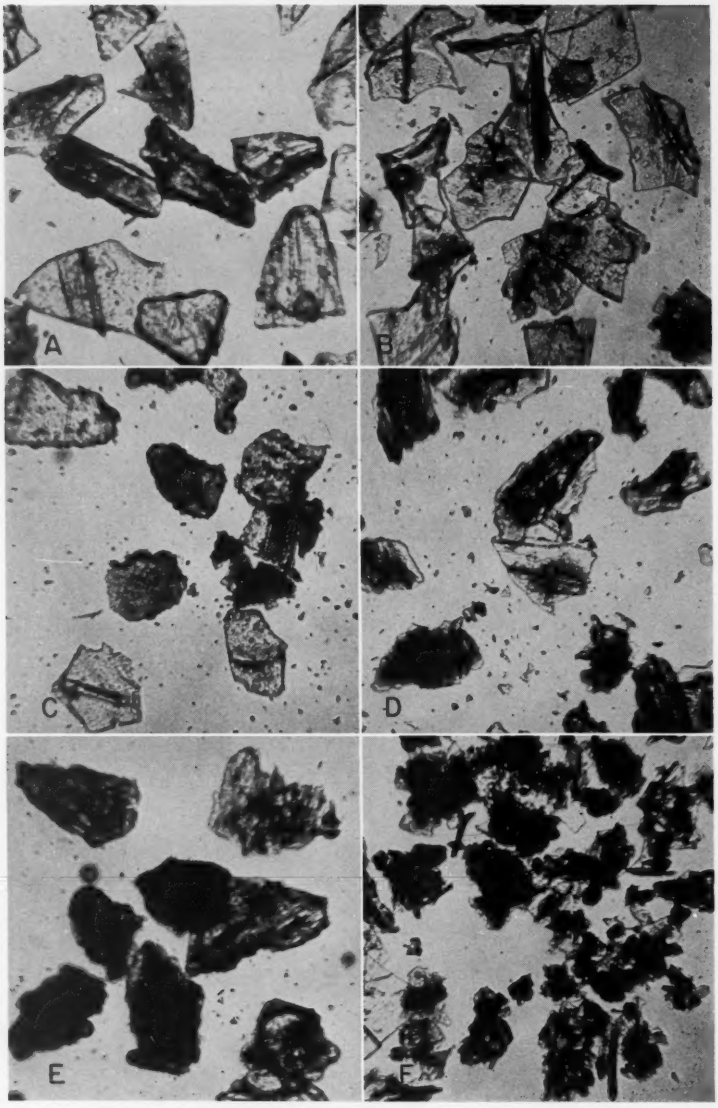

PLATE 1.—Photomicrographs of Miocene volcanic ash shards (88 to 125 micron fraction) mounted in 1.640 index liquid. Plane polarized light; magnification 250×. A, Lower Sand Canyon (loc. 5). B, Box Butte (loc. 4). C, Harrison (loc. 5). D, Spottedtail (loc. 5). E, Gering (loc. 6). F, Upper Sand Canyon (loc. 3).

stratigraphic positions in this member. The lower of these two ash beds has been described from the type locality of the Sheep Creek formation (Matthew and Cook, 1909; Lugn, 1939) and the type locality of the Sand Canyon member (Elias, 1942).

At the Sheep Creek type locality (sec. 30, T. 26 N., R. 55 W., Sioux County, Nebraska, loc. 5, fig. 2) a bed of volcanic ash is exposed along a linear distance of about one-half mile in the canyon heads. Its base occurs 10 feet above the contact of the Sand Canyon member on Spotted-tail member and the ash is overlain by 10 to 15 feet of Sand Canyon beds. Where sampled the ash bed is 36 inches thick, distinctly bedded and cross-bedded, and the bottom one inch is exceptionally coarse.

The type locality of the Sand Canyon member is in sec. 14, T. 29 N., R. 47 W., Dawes County, Nebraska (loc. 3, fig. 2). Here, two beds of volcanic ash are exposed in a road cut and canyon walls. The lower of these two ash beds, which is four to six inches thick, is stratigraphically equivalent to the ash in the lower Sand Canyon in Sioux County, Nebraska, and is designated on the chart (fig. 1) as "lower Sand Canyon ash" whereas the upper of the two is called "upper Sand Canyon ash." The upper ash, which is about 20 feet above the lower bed, is two to four feet thick, dark-gray, cross-bedded, and cemented at the top.

The glass of the lower Sand Canyon ash bed is thick and substantial, with shards of various shapes (pl. 1, A). Some have large vesicles; coarse fibrous shards are also present. The refractive index is relatively high, ranging from a little less than 1.504 to more than 1.511. The index of most shards is between 1.505 and 1.508. The color of the fraction finer than 62 microns is fairly dark—between N 8 and 5YR 8/1.

Chemical analyses of four samples of lower Sand Canyon ash indicate that it is high in Fe_2O_3 (3.34 to 4.02 percent) and in P_2O_5 (0.09 to 0.25 percent) but otherwise not unusual.

The upper Sand Canyon ash differs in several ways from other deposits studied. The shards range in shape from simple to extremely complex and from thin to thick (pl. 1, F). Many shards contain numerous vesicles. The color of the glass ranges from colorless to various shades of brown, giving the sample a salt-and-pepper aspect. The over-all color is between 5Y 5/2 and 10YR 6/2. The refractive index has the greatest range of any glass studied—from 1.506 to 1.564.

Chemical analyses of two samples from the upper Sand Canyon ash bed indicate that the composition of this ash is less silicic than that of the other deposits studied and is somewhat similar to the composition of Daly's (1933) average syenite. The glass is the highest in Al_2O_3, Fe_2O_3, and CaO of any deposits analyzed, and lowest in K_2O. It is relatively high in MgO, P_2O_5, and Na_2O. Despite its intermediate composition and Miocene age, the glass of the samples analyzed seemingly is unaltered.

Box Butte Member.—The Box Butte member of the Sheep Creek formation was named and described by Cady in 1940, and further described by Elias in 1942. In 1946 Cady and Scherer published a measured section of this member from sec. 26, T. 28 N., R. 52 W., Box Butte County, Nebraska (loc. 4, fig. 2), showing the stratigraphic position of a volcanic ash bed. Here the Box Butte member rests directly on the Marsland formation. The volcanic ash bed is two feet thick and occurs six feet below the crest of a small but prominent knob.

The Box Butte volcanic ash bed (pl. 1, B) contains both thick and thin shards, many of which have high-angle bubble junctures. The coarsest and thickest shards are strongly curved, but vesicles in them are rare. The index of refraction of most of the glass is $1.501 \pm .003$. The color of the fraction finer than 62 microns is between N 9 and 5YR 9/1.

Chemical analyses of three samples of this ash show that it is relatively high in silica and low in Fe_2O_3 and TiO_2.

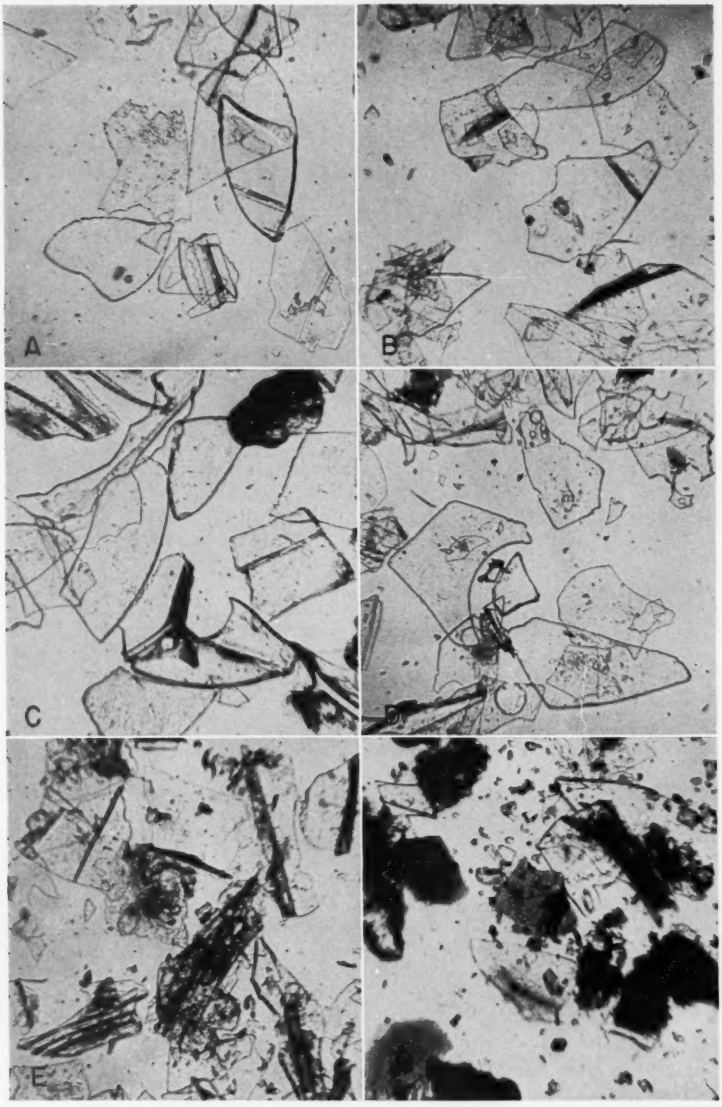

PLATE 2.—Photomicrographs of Pliocene volcanic ash shards (88 to 125 micron fraction) mounted in 1.640 index liquid. Plane polarized light; magnification 250×. A, Calvert (loc. 20). B, Upper ash from Valentine type locality (loc. 1). C, Reager (loc. 29). D, Rawlins (loc. 37). E, Dellvale (loc. 17). F, Fort Wallace (loc. 36). Note biotite.

Ogallala Formation

The Ogallala formation (Pliocene) (Darton, 1889) of the central Great Plains is abundantly supplied with volcanic ash deposits. They are widely distributed geographically and range through more than half the stratigraphic span of the formation. Ogallala volcanic ash from 36 localities in northern Kansas and western Nebraska was studied. The stratigraphy of the Ogallala formation of northern Kansas and its correlation with type sections in Nebraska are being discussed in a separate paper to be published by the State Geological Survey of Kansas. Consequently only the general stratigraphic placement of the various ash falls described herein will be given.

The Ogallala is divided into three recognized members (Kansas classification) in ascending order: Valentine, Ash Hollow, and Kimball. All deposits described here with the exception of four occur within the Ash Hollow member.

Valentine Member.—The Valentine member contains one major ash fall that was studied at three localities in Kansas and one in Nebraska. This ash bed was named the Calvert bed (Carey and others, 1952) from exposures in the commercial mine at Calvert (loc. 20, fig. 2) in Norton County, Kansas (NW¼ SW¼ sec. 25, T. 2 S., R. 22 W.), where it had previously been described by Swineford and Frye (1946) and Frye and A. R. Leonard (1949). At this locality the Calvert bed is 22 feet thick, which is the maximum thickness of any late Tertiary ash studied. In Kansas fresh ash was collected also in the SE¼ SE¼ sec. 25, T. 3 S., R. 25 W., Norton County (loc. 24), and an altered deposit tentatively assigned to this bed was sampled in the NW¼ NW¼ sec. 33, T. 3 S., R. 34 W., Rawlins County (loc. 32). In Nebraska an ash lentil tentatively assigned to the Calvert bed was studied and collected in the type section of the Valentine member (loc. 1). Here the ash occurs as discontinuous, partly cemented lentils a few inches thick 185 feet above the base of the member and about 110 feet above the position of the "Railroad Quarries" from which an abundant fossil vertebrate fauna has been described (Schultz and Stout, 1941).

The index of refraction of most of the shards is about $1.501 \pm .002$. The glass is rather thin and simple with large radius of curvature (pl. 2, A, B). No vesicles were observed. The bubble junctures are characteristically straight, and there is seldom more than one juncture per shard. Megascopically the fresh glass is very sparkling, owing at least in part to the flatness of the individual shards. A few crystals of volcanic quartz are present. The color of the fraction finer than 62 microns is between N 8.5 and 5YR 8/0.5.

Chemical analyses of four samples assigned to the Calvert bed are given in table 2.

In the type section of the Valentine member (NE¼ sec. 17, T. 33 N., R. 27 W., Cherry County, Nebraska, loc. 1, fig. 2) a thin zone of volcanic ash is associated with bentonite beds in silty sands about 75 feet above the base of the member and at the approximate stratigraphic position of the "Railroad Quarries" that have yielded fossil vertebrates (Schultz and Stout, 1941; Johnson, 1936, 1938; Lugn, 1938; McGrew, 1938; McGrew and Meade, 1938). Stratigraphically this ash zone is 110 feet below the position of the Calvert bed in this section.

Because the glass in this deposit is somewhat altered, its refractive index is not determinable. The shape of the shards is fairly simple, but the glass is thick. Some biotite flakes, presumably of volcanic origin, are present.

Chemically the ash contains a rather high percentage of Al_2O_3, Fe_2O_3, and MgO, and it has the highest P_2O_5 content (0.19 percent) of any sample analyzed. It is low in K_2O; perhaps this is attributable to weathering processes.

TABLE 2.—*Chemical composition of 48 volcanic ash samples*

(Analyses in State Geological Survey Geochemistry Laboratory under supervision of Russell T. Runnels)

Locality No.	Bed	Type of sample[1]	SiO_2	Al_2O_3 + MnO_2, Ga_2O_3 if present	Fe_2O_3	TiO_2	CaO	MgO	P_2O_5	SO_3	K_2O	Na_2O	Ignition loss 1000° C. (H_2O+)[2]	Total
16	Reamsville	Comp, 3′ bed	70.88	10.98	2.08	0.21	2.61	0.05	nil	tr	5.52	1.41	6.06	99.35
28	Reamsville	S, 5′ bed	71.98	11.51	1.36	0.88	1.15	0.15	tr	tr	5.12	2.14	5.44	99.73
25	Reager	Ch, basal 2′ of 7′ bed	72.17	11.05	1.61	1.19	0.85	0.19	nil	tr	5.45	1.66	5.15	99.32
10	Reager	Ch, basal 18″ of 3½′ bed	71.45	11.50	2.53	0.62	1.08	0.37	tr	tr	5.14	1.71	5.02	99.42
29	Reager	Comp, 3.2′ bed	71.58	11.37	1.69	1.17	0.83	0.34	tr	nil	5.15	1.91	5.39	99.43
31	Reager	S, basal 1′ of 6′ bed	71.64	11.82	1.68	1.11	0.93	0.27	tr	tr	5.10	2.29	5.14	99.98
23	Dellvale	S, basal 1½″ of 9½′ bed	72.33	11.17	1.29	1.02	0.64	0.17	tr	tr	6.00	2.01	5.02	99.65
21	Dellvale	S, 2½′ bed	72.67	11.28	1.55	0.98	0.79	0.11	tr	tr	5.57	1.54	5.52	100.01
17	Dellvale	Ch, middle 1′ of 2′ bed	73.00	11.31	1.76	0.49	0.97	0.24	nil	tr	6.00	1.79	4.04	99.60
36	Fort Wallace	S, 1.5′ bed	65.88	13.85	2.50	2.18	1.41	1.34	tr[3]	tr	4.16	3.18	5.47	99.97
33	Rawlins	S, 3.5′ bed	71.99	11.48	2.39	0.64	1.04	0.69	nil	nil	4.75	2.28	4.27	99.53
34	Rawlins	S, 1′ bed	71.51	10.93	1.95	0.52	0.49	1.27	nil[3]	tr	5.19	1.48	6.17	99.51
37	Rawlins	S, 3′ bed	71.93	11.57	1.71	0.97	0.72	0.19	tr	tr	5.61	1.81	5.64	100.15
37	Rawlins	S, basal 2″ of 3′ bed	72.05	11.26	1.66	1.22	1.02	0.21	nil	tr	5.03	2.51	5.01	99.97
8	Rawlins?	S, 4′ bed	71.86	11.38	2.87	0.48	0.69	0.18	nil	tr	5.64	1.08	5.39	99.57
14	Unnamed (Ash Hollow)	S, 6″ limestone bed	72.89	11.47	1.29	0.66	0.53	0.20	nil[3]	nil	5.98	1.63	4.81	99.46
15	Unnamed (Ash Hollow)	Ch, basal 4″ of 2′ bed	72.82	11.50	1.26	0.63	0.55	0.11	tr	tr	6.02	3.03	4.56	100.48
13	Unnamed (Ash Hollow)	S, 2′ above base of 8½′ bed	72.46	11.40	1.46	0.75	0.51	0.14	nil	tr	6.24	1.33	5.19	99.48
19	Unnamed (Ash Hollow)	S, 6′ above base of 6½′ bed	72.40	11.11	1.41	0.99	0.70	0.14	nil	tr	5.91	1.51	5.21	99.38
26	Unnamed (Ash Hollow)	Comp, 3′ bed	70.60	11.80	2.50	0.32	1.14	0.39	tr	tr	5.26	1.54	5.61	99.16
26	Unnamed (Ash Hollow)	Ch, basal 1′ of 3′ bed	70.69	11.93	2.59	0.20	1.09	0.39	tr	tr	5.39	1.45	5.58	99.31
7	Unnamed (Ash Hollow)	Ch, basal 16″ of 4′ bed	72.46	11.95	2.04	0.21	1.32	0.94	0.01	nil	4.82	1.94	4.31	99.99
9	Unnamed (Ogallala type)	Comp, lower 4′ of 50″ bed	71.79	11.47	1.98	0.23	1.28	0.31	tr	tr	6.05	1.34	5.62	100.07
9	Unnamed (Ogallala type)	Ch, 18″ to 50″ above base of 50″ bed	71.32	11.35	2.00	0.54	1.39	0.64	tr	tr	5.87	1.05	5.50	99.66
9	Unnamed (Ogallala type)	Ch, 3″ to 18″ above base of 50″ bed	72.02	11.35	1.96	0.40	0.66	tr	nil[3]	tr	6.17	1.34	5.42	99.32
9	Unnamed (Ogallala type)	Ch, basal 3″ of 50″ bed	71.25	11.53	1.88	0.23	1.42	0.27	tr	tr	6.11	1.07	5.73	99.49
2	Unnamed (Ash Hollow)	S, 7.8′ above base of 10′ bed	72.11	11.35	2.28	0.38	0.68	0.24	nil[3]	tr	5.90	1.13	5.17	99.24
2	Unnamed (Ash Hollow)	S, 5.8′ above base of 10′ bed	72.08	11.26	2.27	0.55	0.60	0.37	0.03	tr	5.85	1.15	5.32	99.48
2	Unnamed (Ash Hollow)	S, 2.8′ above base of 10′ bed	72.02	10.95	2.28	0.63	0.55	0.03	nil[3]	tr	6.08	1.08	5.42	99.04
2	Unnamed (Ash Hollow)	S, 0.8′ above base of 10′ bed	71.91	11.46	2.13	0.22	0.42	0.03	tr	tr	6.85	1.45	4.80	99.27
2	Unnamed (Ash Hollow)	S, base of 10′ bed	72.71	11.52	2.45	0.25	0.52	0.04	nil	tr	6.56	1.03	4.99	100.07
20	Calvert	S, 10.5′ above base of 22′ bed	70.05	10.87	1.91	0.55	2.72	0.24	tr	tr	5.71	1.54	5.58	99.17
24	Calvert	Ch, 10′ bed	72.11	11.13	1.50	0.98	1.25	0.10	tr	tr	5.87	1.65	5.46	100.05
1	Calvert?	S, 6″ bed	72.98	10.56	2.08	0.48	0.50	0.06	nil[3]	tr	6.26	1.06	5.29	99.27
1	Calvert?	S, float block from 6″ bed	73.42	10.45	2.08	0.45	0.44	0.07	nil[3]	tr	6.04	1.03	5.44	99.40
1	Unnamed (Valentine, lower bed)	S, 2″ bed	70.81	13.31	3.23	0.51	1.68	0.84	0.19	tr	3.24	1.61	4.14	99.56
4	Unnamed (Box Butte)	Ch, 12″ to 17″ above base of 2′ bed	73.01	10.73	1.76	0.15	1.00	0.25	tr	tr	6.08	1.06	5.51	99.55
4	Unnamed (Box Butte)	Ch, 6″ to 10″ above base of 2′ bed	72.41	11.53	1.68	0.23	0.61	0.29	tr	nil	6.50	0.93	5.29	99.47
4	Unnamed (Box Butte)	Ch, basal 6″ of 2′ bed	74.82	10.16	1.56	0.24	0.73	0.21	0.03	tr	5.56	1.05	4.87	99.20
3	Unnamed (Sand Canyon, upper bed)	S, 2½′ above base of 40″ bed	59.14	16.14	6.44	0.77	4.69	1.80	0.16	tr	3.08	2.16	5.59	99.97
3	Unnamed (Sand Canyon, upper bed)	S, base of 40″ bed	60.89	14.84	5.78	1.10	4.03	1.94	0.14	nil	3.41	2.20	5.42	99.75
5	Unnamed (Sand Canyon, lower bed)	Ch, 14″ to 24″ above base of 32″ bed	70.17	11.39	4.02	0.41	1.05	0.09	0.13	nil	6.02	1.13	5.30	99.71
5	Unnamed (Sand Canyon, lower bed)	Ch, basal 12″ of 32″ bed	69.96	11.61	3.54	0.41	0.89	0.09	0.10	nil	6.09	1.22	5.55	99.44
5	Unnamed (Sand Canoyn, lower bed)	S, basal 1″ of 32″ bed	69.29	11.79	3.67	0.66	1.19	0.25	0.10	nil	5.28	2.58	4.80	99.61
5	Unnamed (Sand Canyon, lower bed)	S, base of 3′ bed, ¼ mi. W. of S.C.	70.16	11.54	3.34	0.24	1.43	0.21	0.17	tr	5.81	1.08	5.41	99.39
5	Unnamed (Spottedtail)	S, 6″ bed	68.39	12.83	1.83	0.16	2.10	0.34	0.09	tr	6.67	1.72	5.93	100.06
5	Unnamed (Harrison)	S, 4′ bed	68.12	12.42	1.79	0.16	1.66	2.09	0.02	tr	5.50	1.38	6.37	99.51
6	Unnamed (Gering)	S, 1½″ bed	69.09	13.09	1.82	1.33	1.76	1.98	tr	tr	3.97	2.30	4.97	100.31

[1] Comp, composite sample; S, spot sample; Ch, channel sample.

[2] Sample dried at 105° C.

Ash Hollow Member.—Volcanic ash deposits in the Ash Hollow member (Engelmann, 1876; Lugn, 1938, 1939) were studied and sampled at 28 localities in northern Kansas and four localities in Nebraska. Although seven of these deposits have not been given formal stratigraphic recognition, the others have been grouped on the basis of petrographic characters and related stratigraphy into five beds which are assigned formal names. These named beds are, in ascending order, Rawlins, Fort Wallace, Dellvale, Reager, and Reamsville.

Rawlins ash bed: The Rawlins ash bed, including seven localities in Kansas and one in Nebraska, is named from exposures at the center of the west line SW¼ sec. 4, T. 4 S., R. 34 W., Rawlins County, Kansas (loc. 33, fig. 2). At the type locality 3½ feet of ash is exposed. The basal two feet is relatively pure and massive whereas the upper 1½ feet is interbedded with fine to medium sand. Ten feet of fine sand, silt, and clay is exposed below the ash bed and cemented silty sandy marl one foot thick overlies the ash.

The other Kansas localities from which the Rawlins ash bed is described are: SE¼ SE¼ sec. 20, T. 5 S., R. 36 W., Rawlins County (loc. 34); NE¼ SE¼ sec. 27, T. 4 S., R. 23 W. (loc. 22); NE¼ NE¼ sec. 16, T. 2 S., R. 21 W. (loc. 18) (where the ash constitutes the clastic particles in a limestone bed), Norton County; NE¼ NW¼ NE¼ sec. 30, T. 1 S., R. 19 W., Phillips County (loc. 12); NE¼ NW¼ sec. 10, T. 5 S., R. 29 W., Decatur County (loc. 27). In the SE¼ SE¼ SE¼ sec. 8, T. 14 S., R. 38 W., Wallace County (Elias, 1931), three feet of Rawlins ash bed is exposed seven feet above the Pierre shale (loc. 37); the lowermost two inches is coarser and petrographically distinct from the remainder of the bed. In Nebraska ash tentatively assigned to the Rawlins bed was sampled from the type section of the Ash Hollow member, south of Lewellen, where four feet of volcanic ash occurs 180 feet below the top of the type section (loc. 8).

The index of refraction of most of the glass in the Rawlins bed is about 1.502 to 1.503±.002. The shards, which are not as flat or simple as those of the Calvert bed, are rather thin with common straight, parallel junctures. Many of the shards have large circular or elliptical holes (pl. 2, D).

The glass of the lower two inches of the Rawlins bed in the Wallace County locality has a slightly higher index of refraction (n=1.503 to 1.506±.002) and is thicker than the typical Rawlins glass. Vesicles are present in some shards, but no circular holes were observed. The chemical composition of the basal glass is similar to that of the other three Rawlins samples analyzed (table 2).

Fort Wallace ash bed: The Fort Wallace ash bed is known only from two localities, both in Wallace County, Kansas. It is named from exposures south of old Fort Wallace in tributary canyons along the south side of Smoky Hill River valley in the west line SW¼ sec. 7, T. 14 S., R. 38 W., where 1½ feet of ash occur 29 feet above the Ogallala-Pierre shale contact and 65½ feet below the top of the "Algal limestone" (loc. 36). It was also sampled from a one-foot bed in the NE¼ NE¼ sec. 16, T. 14 S., R. 40 W. (loc. 35).

The chief petrographic feature which distinguishes the Fort Wallace ash from most other beds is the large quantity of biotite which it contains (pl. 2, F). In the coarser size fractions biotite constitutes as much as five percent of the sample. A trace of sanidine is also present. The shape of the glass is not uniform: most shards are thin, but thick glass is also fairly common. Most of the bubble junctures are straight, and there are some coarsely fibrous shards. Groups of vesicles are common. The color of the fraction finer than 62 microns is somewhat darker than 10YR 8/2, owing to the abundant biotite. The refractive index of the glass is high, ranging from 1.507 to 1.515, with most shards having an index of 1.511±.002. The samples are contaminated with secondary calcium carbonate.

1 Comp, composite sample; S, spot sample; Ch, channel sample.

Chemical analysis of a sample from which the calcium carbonate had been removed by treatment with cold dilute HCl indicates that this ash is somewhat low in silica and slightly high in Al_2O_3, Fe_2O_3, and MgO. The content of Na_2O (3.18 percent) is the highest of any sample analyzed. The most unusual chemical feature of this ash, however, is its high TiO_2 content (about two percent). No titanium minerals are identified microscopically; the titanium seemingly is part of the glass.

Dellvale ash bed: The Dellvale ash bed is named from exposures in the NW¼ NW¼ sec. 2, T. 4 S., R. 24 W., southeast of Dellvale, Norton County, Kansas (loc. 23). At this locality 9½ feet of volcanic ash occurs within silts and sandy silts which overlie a thick fossiliferous sand and gravel bed. This ash bed is also well exposed in the Almena section (Frye and A. R. Leonard, 1949) in Norton County (loc. 21) and in the NE¼ NE¼ sec. 19, T. 2 S., R. 18 W., Phillips County, Kansas (loc. 17).

Most of the glass of the Dellvale bed has a refractive index of 1.500 to 1.501 ±.002. The glass is very thin, and many shards contain several long, straight, and parallel junctures (pl. 2, E). No vesicles were observed. The color of the fraction finer than 62 microns is 5YR 9/1.

Chemical analyses of three samples of Dellvale ash are reported in table 2.

Reager ash bed: Four localities of Reager ash bed were studied in Kansas. The bed is named from exposures in an abandoned commercial pit in the SW¼ SE¼ sec. 2, T. 3 S., R. 25 W., southeast of Reager, Norton County, Kansas (loc. 25, fig. 2) where the bed is seven feet thick and is exposed for about one-fourth mile along a minor canyon. This bed was also sampled in Kansas in the SE¼ SE¼ sec. 16, T. 1 S., R. 21 W., Norton County (loc. 10); the NE¼ NE¼ sec. 15, T. 3 S., R. 30 W., Decatur County (loc. 29); and the SW¼ SE¼ sec. 2, T. 3 S., R. 33 W., Rawlins County (loc. 31), where the Reager bed is directly overlain by a weathered, impure ash tentatively assigned to the Reamsville bed.

Most of the glass in the Reager bed has a refractive index of 1.502 to 1.503 ±.002. The shards are simple, with a few long parallel junctures and some high-angle junctures (pl. 2, C). Most of the shards are moderately thick. Traces of biotite are present. The color of the fraction finer than 62 microns is about 7.5YR 8/1.

Chemical analyses of Reager ash from four localities are shown in table 2. The glass seemingly is lower in Fe_2O_3 and higher in TiO_2 than the average Ogallala ash.

Reamsville ash bed: The Reamsville bed is the highest named ash bed in the Ogallala formation of the central Great Plains region. It occurs slightly above the middle of the Ash Hollow member. It is named from exposures along Kansas Highway 8 in the center of the west line SW¼ sec. 32, T. 1 S., R. 14 W., Smith County, Kansas, west-southwest of Reamsville (loc. 16, fig. 2). At this locality three feet of volcanic ash occurs in a sequence of partly cemented sand and silty sand. This bed was studied also in the SE¼ SW¼ sec. 8, T. 4 S., R. 29 W., Decatur County, Kansas (loc. 28); the NW¼ SW¼ sec. 31, T. 1 S., R. 19 W., Phillips County (loc. 11); and the SW¼ SE¼ sec. 2, T. 3 S., R. 33 W., Rawlins County (loc. 30) where weathered Reamsville ash directly overlies fresh Reager ash.

The refractive index of the glass of the Reamsville bed is somewhat lower than that of most of the glass studied, and it has a slightly greater range (n = 1.497 to 1.502 ±.002). The shards are nearly flat to strongly curved or fibrous; their shape is characteristically rather complex with many junctures. Vesicles are common. The glass is only moderately thick, and the shards are not generally elongate. The color of the fraction finer than 62 microns is slightly paler than 5YR 8/1.

Chemical analyses of Reamsville ash from localities 16 and 28 are shown in table 2.

Unnamed lentils: Volcanic ash falls that lack wide occurrence and stratigraphic significance are not assigned formal names. In this category are six volcanic ash exposures in the Ash Hollow member in Kansas and three in Nebraska. In so far as possible these will be discussed in stratigraphic order.

At the type locality of the "Burge channel" (center of east half of sec. 15, T. 32 N., R. 30 W., Cherry County, Nebraska, loc. 2) 10 feet of volcanic ash is exposed. As the base of the volcanic ash bed is approximately 45 feet above the top of the vertebrate-fossil-bearing "Burge sands" (Johnson, 1936) this ash bed is placed within the lower part of the Ash Hollow member of the Ogallala formation.

The glass of the Burge ash is rather thick, and the shape of the shards in the finer fractions is simple. Many coarse shards have multiple straight junctures. No vesicles were observed. The refractive index is uniform and in most of the shards is $1.502 \pm .002$. The color of the fraction finer than 62 microns is between 5YR 8/1 and N 8.

The chemical composition, as shown by five analyses, shows no unusual concentrations of constituents.

An impure, partly cemented volcanic ash lentil is exposed in a road cut and canyon side just above flood-plain level about 0.8 mile north of Lisco, Nebraska (loc. 7, fig. 2). This ash bed is about four feet thick; its stratigraphic position within the member is not firmly established.

The glass is somewhat altered so that the shard outlines are anisotropic and the refractive index is not determinable. The glass is thick, with many and complex bubble junctures. Vesicles of all types are common. A small quantity of biotite (probably volcanic) is present. The color of the fraction finer than 62 microns is about 5Y 8/1 and is due in part to alteration of the glass.

In chemical composition the ash has a slightly high MgO content.

Two feet of volcanic ash in the Ash Hollow member is exposed somewhat below the stratigraphic position of the Dellvale ash bed in the $NE\frac{1}{4}$ $NE\frac{1}{4}$ sec. 19, T. 2 S., R. 18 W., Phillips County, Kansas (loc. 15, fig. 2). Volcanic ash with similar petrographic characteristics is exposed in the $SW\frac{1}{4}$ $SW\frac{1}{4}$ sec. 14, T. 1 S., R. 18 W., Phillips County (loc. 14). At this locality the ash occurs as the clastic particles in a limestone bed approximately half a foot thick.

Except for its slightly greater thickness, the glass in these two deposits is nearly indistinguishable petrographically from the glass of the Reamsville bed. Chemical analyses of the two samples are given in table 2.

Two exposures of volcanic ash in the $NW\frac{1}{4}$ $NE\frac{1}{4}$ sec. 12, T. 3 S., R. 22 W., Norton County (loc. 19, fig. 2) and the $SW\frac{1}{4}$ $NE\frac{1}{4}$ sec. 3, T. 2 S., R. 19 W., Phillips County, Kansas (loc. 13), are similar petrographically. On the basis of fossil seeds the stratigraphic position of this fall is judged to be near the top of the lower third of the member. At the Norton County locality the ash is $6\frac{1}{2}$ feet thick; in Phillips County it is eight feet thick and is interbedded with thin beds of silt and fine sand.

The shards in this ash bed are thin, fairly flat, and simple. Junctures, where present, are straight, and multiple-junctured shards are uncommon. The refractive index of 90 percent of the fresh shards is $1.501 \pm .003$. The color of the fraction finer than 62 microns is 5YR 8/0.5.

Chemical analyses of samples from this bed (table 2) suggest that the glass is slightly lower than average in Fe_2O_3 and Na_2O.

In the $SE\frac{1}{4}$ $SW\frac{1}{4}$ sec. 25, T. 2 S., R. 25 W., Norton County, Kansas (loc. 26, fig. 2), approximately $3\frac{1}{2}$ feet of volcanic ash is exposed along a creek bank; this ash is present also in section 36. This bed occurs stratigraphically between

the Dellvale and Reamsville beds, and was erroneously included by Carey and others (1952) in the Reager bed.

The glass in this deposit is fairly fresh and moderately thin, with straight parallel and high-angle junctures. It contains few or no vesicles. The refractive index of most of the glass ranges from 1.504 to 1.507 and is predominantly $1.505 \pm .001$. The color of the fraction finer than 62 microns is about 5YR 9/1. Chemical analyses of two samples of this ash show that it is moderately high in Fe_2O_3 (2.50 and 2.59 percent, respectively) and low in TiO_2.

At the type locality of the Ogallala formation on Feldt ranch east of Ogallala, Nebraska (loc. 9, fig. 2), four feet of volcanic ash is exposed about 31 feet above the base of the local section and 65 feet below the top of the local Ogallala section. Although the stratigraphic position of this ash fall is not firmly fixed it is judged to occur in the middle one-third of the Ash Hollow member.

Most of the glass is fairly thin, but a few thick shards are present. Straight, closely spaced, parallel junctures are common, but only a few long vesicles were observed. The index of refraction of the glass is 1.500 to $1.504 \pm .002$. The color of the fraction finer than 62 microns is slightly paler than 5YR 8/1.

Chemical analyses of four samples from this bed are given in table 2. The glass is somewhat high in K_2O content and low in Na_2O.

Volcanic ash was collected from a locality in the $NE\frac{1}{4}$ $NE\frac{1}{4}$ $NE\frac{1}{4}$ sec. 2, T. 7 S., R. 24 W., Graham County, Kansas (loc. 38, fig. 2); the stratigraphic position of this ash is not determined even as to its inclusion within the Ash Hollow member. In this exposure thin zones of ash occur interbedded with thin crenulate beds of sand and silt that are partly cemented with calcium carbonate. Although constituting less than half of the sediment volumetrically the ash is distributed through a five-foot interval.

Petrographically this ash is characterized by a few percent of volcanic biotite, a trace of sanidine, and rather large quantities of unidentified crystalline aggregates (presumably cryptocrystalline feldspars and quartz from devitrification of glass). The glass has a somewhat lower refractive index ($n = 1.501$ to 1.510; most $= 1.504 \pm .002$) than that of the Fort Wallace ash. The shards are of various shapes, but no fibrous shards were observed, and there are very few vesicles in the glass. The color of the fraction finer than 62 microns is about 10YR 7/2.

Chemical Character of the Ash Beds

Samples chosen for analysis were those in which the glass was relatively fresh and unaltered, and which contained only small quantities of detrital (nonvolcanic) contaminants. Samples were purified by screening and choosing only those size fractions which microscopic examination showed to be at least 95 percent volcanic origin.

Samples that contained large quantities of calcite were treated for a few minutes with cold dilute HCl, washed, and dried before chemical analysis. There is no evidence that the acid treatment affected the composition of the glass, although presumably it may have removed some adsorbed cations. All samples were dried at 105° C. before analysis.

The arrangement of chemical analyses in table 2 is in approximately chronological order, from youngest to oldest.

With the exception of the Fort Wallace, Sand Canyon, Spottedtail, Harrison, and Gering samples, the chemical composition is quite uniform. The SiO_2, Al_2O_3, K_2O, and H_2O content of most samples is remarkably similar.

Silica.—The mean silica content of the 48 samples is 71.03 percent; standard deviation is 2.78. Although SiO_2 is one of the constituents most likely to be affected by alteration or contamination, the three samples containing the least silica (upper Sand Canyon and Fort Wallace) are seemingly unaltered and

petrographically distinct from the other samples, and they are judged to have been deficient in SiO_2 originally.

Alumina, ferric oxide, titania, and phosphorous pentoxide.—The mean R_2O_3 content ($Al_2O_3+Fe_2O_3+TiO_2+P_2O_5$) is 14.57 percent; standard deviation is 2.07. R_2O_3 ranges from 12 to 15 percent in all samples except most of those which are abnormally low in SiO_2. Although R_2O_3 increases with decrease in SiO_2, there is no petrographic evidence to suggest that R_2O_3 content is related to degree of alteration of the glass. With two exceptions, measurable amounts of P_2O_5 are found only in samples which are older than Ash Hollow.

Alkaline Earths.—The mean CaO content in the 48 samples is 1.17 percent; standard deviation is 0.85. Only a small part of this variation is due to secondary calcite. The mean MgO content is only 0.43 percent; standard deviation is 0.54. Variation in MgO among samples from the same bed is great. This possibly may be attributed to cation exchange between the glass and the water with which it was in contact. The same may be true also for other divalent cations (Fe^{2+} and Ca^{2+}) and for Na^+.

The MgO content of the volcanic ash is much lower than that of bentonite. The mean MgO in 12 bentonites reported by Kerr, Hamilton, and Pill (1950) is 3.58 percent, and the mean in 28 bentonites reported by Ross and Hendricks (1945) is 4.56 percent. It has been suggested (Grim, 1953) that in order to alter to montmorillonite, ash must have a moderate content of MgO, since ash devoid of magnesia does not seem to alter to montmorillonite. Keller, Kiersch, and Howell (1954) show that Mg^{2+} ions are added during alteration of vitric tuff to bentonite. The present data (i.e., variation of MgO in glass within any one bed) suggest the possibility that Mg^{2+} may be added by ion exchange before devitrification of the glass. Furthermore, the large numbers of vitric ash lentils and correspondingly rare bentonites in the late Tertiary deposits of the central Great Plains simply may reflect nonmarine conditions of deposition and a relatively low concentration of Mg^{2+} in the water in which the ash was deposited. Most of the known bentonites of the Ogallala formation in Kansas are restricted to the Valentine member, which occurs only in valleys cut in marine sediments of Cretaceous age.

Alkalies.—The mean K_2O content in the 48 samples is 5.53 percent; standard deviation is 0.83. The K_2O in all except five samples (three of which are from the exceptional Fort Wallace and upper Sand Canyon lentils) is within the range 4.75 to 6.85 percent. Na_2O, on the other hand, shows much variability, even among samples from the same locality. The mean Na_2O content is 1.62 percent; standard deviation is 0.54. The coefficient of variation ($\sigma/\overline{X}$) for K_2O is 15.0 percent, whereas that for Na_2O is 33.5 percent. The greater variation of Na_2O than K_2O within a single bed possibly is attributable to the greater mobility of the smaller Na^+ ion.

In no sample is the total alkali content less than 4.85 percent. This seems to be strong evidence that appreciable leaching has not taken place.

Loss on Ignition.—Inasmuch as the samples contained little or no carbonate mineral, the values listed under "ignition loss" are assumed to represent predominantly water, or hydrogen-bonded or monomeric OH (Keller and Pickett, 1954) and perhaps CO_2 and F, which were a part of the glass. The mean water content of the 48 samples is 5.27 percent; standard deviation is only 0.48. The coefficient of variation is 9.1 percent—less than that of K_2O. Most published analyses of volcanic glass indicate less than four percent water (cf. Clarke, 1924, p. 439, analyses A, C, F, and H), although as much as 12 percent water has been found in volcanic glass (Johannsen, 1932). Keller and Pickett (1954) in their summary of published information on the water content of volcanic glasses,

report that the average water content of 41 samples of obsidian is 0.53 percent, and that the range of water content in pitchstones is from less than five percent to more than 10 percent and in perlites from 2.93 to 4.35 percent.

The nearly constant high value for water content in the 48 samples of volcanic ash, despite other variations in composition, suggests that water was probably a determining explosive factor in the production of vesicular ash rather than dense glass and that the original content of water (and dissolved gas) before vesiculation must have been much greater, and probably largely "uncombined." Addition of water after solidification is also a possibility. Another critical explosive factor may be the consistently large quantities of alumina and potassium which tend to increase viscosity of glass (Morey, 1938) and the low percentage of Na_2O.

The general chemical character of the ash and its comparison with the chemical composition of bentonites are summarized in table 3 and figure 3.

The uniformity of composition of the ash may be due to one or more of three factors: (1) common source, (2) selectivity by explosive character, and (3) selectivity by differential alteration of ash beds.

The importance of the source cannot be evaluated from the present data. If all the deposits were from the same source, a progressive chronological change in composition might be expected; this is not observed. It is safe to assume, however, that many of the ash falls have the same origin. The scarcity of bentonites in the section, and the general absence of alteration in some of the less silicic glass, suggests that there was little or no selectivity by differential alteration. The low coefficient of variation for H_2O and some other constituents (table 3) may point to their importance in causing explosive eruptions.

CONCLUSIONS

Late Cenozoic ash falls recorded in the central Great Plains region display no regular or progressive change in character of the ash. All the deposits studied are predominantly vitric tuffs, although some contain minor quantities of biotite, and a few have traces of volcanic quartz and sanidine.

The ash falls have been differentiated qualitatively by slight differences in index of refraction, shape and thickness of shards, and other characters.

The volume and rate of ash falls in this region have not been evenly distributed through time. With the exception

TABLE 3.—*Arithmetic mean* ($\bar{X}$), *standard deviation* (σ), *and coefficient of variation* (V) *of chemical constituents of late Tertiary volcanic ash compared with bentonite*

	Volcanic ash (48)			Bentonite[1] (28)			Bentonite[2] (12)		
	$\bar{X}$	σ	V	$\bar{X}$	σ	V	$\bar{X}$	σ	V
SiO_2	71.03	2.783	3.92	51.85	2.268	4.37	53.46	3.896	7.29
R_2O_3	14.57	2.067	14.18	20.96	3.914	18.67	20.37	2.628	12.90
MgO	0.43	0.545	125.36	4.56	1.642	36.01	3.58	1.144	31.96
CaO	1.17	0.850	72.49	1.45	0.823	56.75	1.29	0.954	73.98
K_2O	5.53	0.831	15.03	0.42[3]	0.283	67.43	0.31	0.198	63.97
Na_2O	1.62	0.541	33.47	1.02[4]	1.107	108.53	0.53	0.611	115.26
H_2O	5.27	0.482	9.14	7.60[5]	2.058	27.08	8.79	3.410	38.79

[1] Ross and Hendricks, 1945.
[2] Kerr, Hamilton, and Pill, 1950.
[3] Reported in 20 analyses.
[4] Reported in 21 analyses.
[5] Reported in 18 analyses.

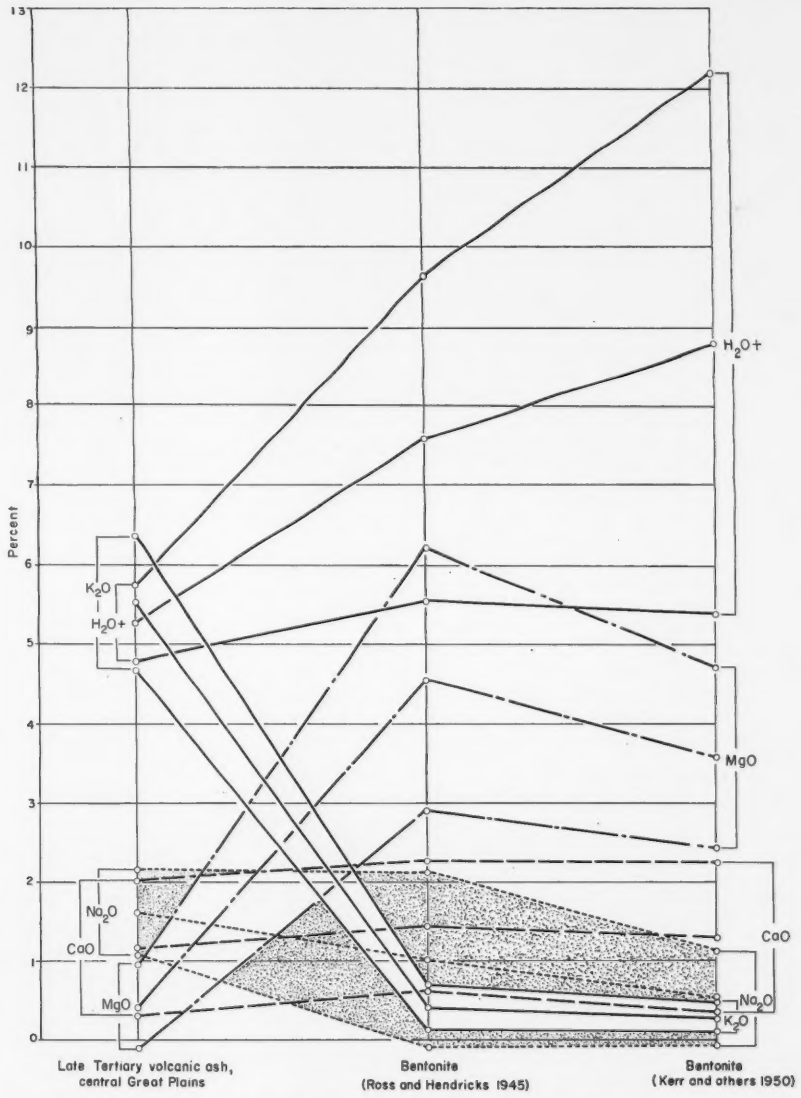

FIG. 3.—Comparison of minor constituents of late Tertiary volcanic ash with those in published analyses of bentonite. Width of band represents one standard deviation on either side of mean value.

of the lower part of the Sand Canyon member, Sheep Creek formation, the contribution of volcanic sediment to total lithology of the Miocene units has been relatively insignificant, whereas an estimated three percent of the volume of Valentine and Ash Hollow members of the Ogallala formation in northern Kansas is volcanic sediment. The greatest frequency of volcanic ash falls occurs in the lower half of the Ash Hollow member. In this interval there are at least eight recorded ash falls, four of which have been assigned formal names (Rawlins, Fort Wallace, Dellvale, and Reager). Eight petrographically distinct ash falls have been described from pre-Ash Hollow Tertiary deposits of Kansas and Nebraska.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 262–269
FIGS. 1–7, DECEMBER, 1955

MICROFABRICS OF TILL FROM OHIO AND PENNSYLVANIA

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ABSTRACT

Microscopic study of oriented thin sections of Wisconsin till from northeastern Ohio and northwestern Pennsylvania reveals three principal types of microfabrics. These fabrics are: (1) microfoliation, (2) coarse fragment orientation, and (3) veining.

Microfoliation appears due to roughly parallel arrangement of silt flakes and elongate silt grains. Perfection of orientation generally decreases as the number of sand size particles increases. Microfoliation is roughly horizontal in till outcrop.

Coarse fragment orientation is well developed in the more sandy till, and is particularly striking where small fragments of coal are involved. Studies indicate that coarse fragment orientation is parallel to microfoliation.

Veining is a structure in which small thin veins or bands rich in silt flakes traverse the rock. Silt flakes roughly parallel vein walls, and veins may occur parallel to microfoliation or may cut it at a large angle. Branching and braided vein patterns are common. It is clear that veins postdate microfoliation. Veins are believed due to shearing of the till. The origin of the microfabrics is considered in detail, and problems worthy of further consideration are suggested.

INTRODUCTION

Fabrics in glacial tills have been known for many years but greatest emphasis has been placed on larger-scaled features (for example see Holmes, 1941). We have not been able to find reference to any study of the small-scale features or microfabrics.

All till specimens were taken from zones IV (unleached, oxidized) and V (unleached, unoxidized) and are representative of the Tazewell, Early Cary, and Late Cary substages (White, 1953a). Thirty-five samples were collected (fig. 1) as oriented blocks, and from each three mutually perpendicular thin sections were prepared. Sections were cut parallel to the horizontal plane, the north-south vertical plane, and the east-west vertical plane. All thin sections were prepared by G. S. Rev. The writers did not have the opportunity to check the thin sections against the original sample blocks to confirm the orientation.

In this paper only three microfabrics will be considered: (1) microfoliation, (2) coarse fragment orientation, and (3) veining. With aid of three mutually perpendicular thin sections per sample, the spatial relations of these three microfabrics were determined. Linear trends in thin section were measured for each structure at numerous places over the slide, and average values were used to prepare block diagrams illustrating three-dimensional relationships.

MICROFOLIATION

The tills are composed largely of a silty matrix in which are embedded sand and small pebbles. The matrix constituents are of two types. One type consists of micaceous minerals, averaging about 0.03 mm, which will be referred to as silt flakes. The identity of these flakes is not yet known, but they are probably mostly mica with some chlorite. Considerable clay material is intermixed (J. B. Droste, personal communication). The second type of constituent is composed largely of quartz, potash feldspar, plagioclase, and calcite, but numerous heavy minerals in small quantities are also present. This second type of constituent occurs generally as subangular and slightly elongate grains of silt size (0.02–0.06 mm), and will hereafter be referred to as silt grains.

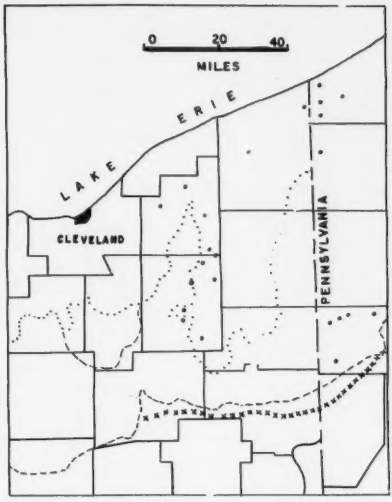

FIG. 1.—Location of samples and position of drift borders in northeastern Ohio (White, 1953a, pl. 26) and northwestern Pennsylvania. Crossed line = Illinoian; dashed line = Early Cary; dotted line = Late Cary; large dots = sample locations.

Grains of quartz and feldspar of very fine sand size (0.0625–0.125 mm) are abundant in most sections, but it seems advisable not to consider these as part of the till matrix. Consequently they are grouped with the coarse sand and pebbles.

Under medium magnification the silt flakes appear to weave between the silt grains in a mesh-like pattern, giving the till matrix a felted texture. Higher magnification clearly reveals that the texture is only slightly decussate and that a preferred orientation exists for both types of matrix constituents (fig. 2). The average section shows most silt flakes are oriented within 10 or 20 degrees of a common direction. Highly elongate silt grains exhibit very perfect parallelism. The length-breadth ratio of these silt grains is commonly 5:1, and, even where as low as 1.5:1, dimensional parallelism is conspicuous. The perfection of dimensional orientation of silt flakes is in large part related to the shape and orientation of silt grains. When silt grains are highly elongate and well-oriented, a higher percentage of silt flakes assumes parallel orientation. Microfoliation is the name given to this aggregate parallelism of silt flakes and silt grains.

Most thin sections, when rotated between crossed nicols, show two principal extinction positions for the till matrix. This directive fabric or microfoliation is more strikingly brought out when the gypsum plate is inserted. Upon rotation a field predominantly yellow changes to a field predominantly blue. Knowing that the sign of elongation of the silt flakes is positive, it is relatively simple to determine both the direction and perfection of microfoliation. Systematic measurements throughout each thin section show a rather uniform trend for microfoliation. Deviations of 10–20 degrees over distances of a few millimeters, however, are not uncommon.

Microfoliation varies in perfection with rock type, being best developed in

FIG. 2.—Silt matrix of till showing preferred orientation of silt flakes and elongate silt grains (stippled). Diameter of circle about 0.2 mm.

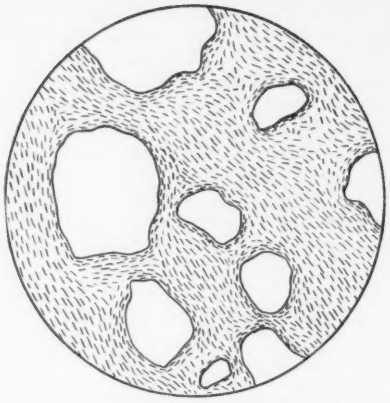

FIG. 3.—Microfoliation of till wrapping around sand particles. Each sand particle is encased in a thin shell of concentric microfoliation. Diameter of circle about 0.5 mm.

the silty till and poorly developed in the sandy till. Even where small quantities of very fine sand are present, microfoliation is noticeably less perfect. The perfection of orientation continues to decline as the sand grains increase in size and abundance.

In the highly sandy tills the orientation of silt flakes bears a conspicuous relation to the shape of the larger fractions. Each sand grain is surrounded by a shell (0.03–0.10 mm thick) of tangentially arranged silt flakes (fig. 3). If elongate silt grains are present, they too are arranged tangentially to the larger sand grain. Each sand grain, therefore, is incased in a fine matrix with pronounced concentric microfoliation which is most pronounced at the contact with the core fragment. Passing outward, the concentric structure fades or gradually assumes the trend for the thin section as a whole. If these large fragments are abundant and closely spaced, the finer till matrix is consumed almost entirely in making up the concentric foliated shells, and no preferred orientation for the thin section as a whole is to be observed.

In the somewhat less sandy till, microfoliation is clearly defined but highly irregular in distribution and trend. It is most perfect in those portions relatively free of large fragments. The foliated streaks wend discontinuously across the thin section, and die out or become deflected as they approach large grains. Streaks commonly bifurcate in the vicinity of sand grains; others are observed to spread around large grains in augen fashion (fig. 4). The small triangular patches at the augen corners show a felty texture, but the silt flakes within a short distance of the sand grain are oriented to complete the encircling shell of tangentially oriented particles.

COARSE FRAGMENT ORIENTATION

Many thin sections show a conspicuous dimensional orientation of coarse fragments. This structure is very striking in the case of coal fragments and may be seen with the naked eye. Microscopically the smaller elongate fragments of coal, other rock particles, and quartz grains also show a very uniform orientation. Microscopic examination of a number of

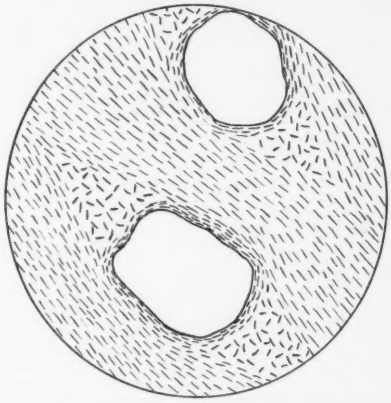

FIG. 4.—Microfoliation of till wrapping around sand particles in augen fashion. Each augen core is encased in a thin shell of concentric microfoliation. Augen corners show decussate texture. Diameter of circle about 0.5 mm.

FIG. 5.—Microfoliation transected by veins (light bands) at about right angles. Microfoliation is made conspicuous by parallel orientation of the tiny elongate particles. (Crossed nicols, with gypsum plate, about ×90.)

thin sections shows that coarse fragment orientation is parallel to microfoliation.

VEINING

In addition to microfoliation many thin sections show distinct structure here referred to as "vein structure" (fig. 5). Individual veins average about 0.1 mm wide and 20–30 mm long. Usually they are not uniformly distributed, but occur in groups with parallel, braided, or branching pattern (fig. 6). The veins may parallel the microfoliation or cut it at various angles. Veins are commonly discontinuous, very irregular, and rarely in echelon.

The best developed veins have a more perfect orientation of silt flakes than does the microfoliation. Though silt flakes are generally parallel to vein trends, they commonly lie at a small angle (up to 20 degrees) to the vein walls giving a definite en echelon arrangement. All gradations occur between clean-cut veins and patches of matrix with small scattered groups of parallel silt flakes. Well-formed veins may terminate abruptly or pass gradually into discontinuous patches or discrete silt flakes. High magnification indicates the vein constituents are mostly silt flakes with considerable silt grains. In brief, the vein material resembles that of the neighboring till matrix.

Some veins cutting microfoliation resemble slip cleavage in slates and phyllites. Each vein may appear as the locus of a sharp flexure or jog in microfoliation,

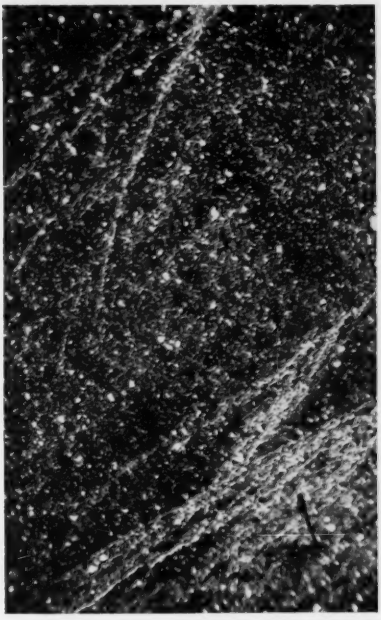

FIG. 6.—Veins (light bands) roughly parallel to microfoliation, showing branching and braided pattern. (Crossed nicols, with gypsum plate, about ×45.)

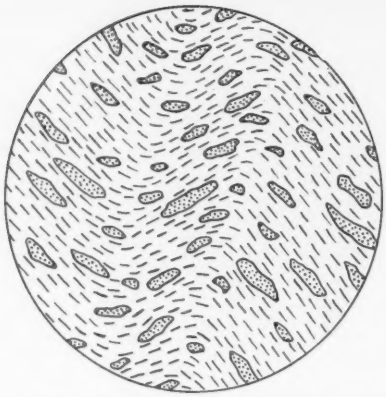

FIG. 7.—Sharp flexure in microfoliation of till revealed by trend of elongate silt grains (stippled) and silt flakes (dashes). More intensely flexed zones appear as veins transecting microfoliation.

resembling drag produced along fault planes (fig. 7). Where flexing is sufficiently sharp, vein minerals trend parallel to the vein walls, but usually an oblique trend is observed. Rotation between crossed niocls, particularly with the gypsum plate, shows the gradual change in trend from the microfoliated till into the center of the vein and a reversal in trend from the vein outward on the opposite side.

Some veins cutting microfoliation show rather well-defined walls with little or no flexing or drag effect at their margins. Veins seldom deviate around sand grains, but appear to terminate before reaching them. Upon approaching large obstructing particles, the vein minerals tend to wrap more in parallelism with the contacts of the sand grains. As more and more flakes conform to the new orientation, the veins appear to fade out.

ORIGIN OF MICROFOLIATION

The shells of concentric microfoliation enclosing sand fragments indicate a buttressing action by large rigid grains against a dense and more plastic till matrix. Such features are to be expected under conditions of simple isotropic compaction, but such is not the case for a directive fabric or microfoliation. Most thin sections containing sand grains, however, show at least some preferred orientation of the matrix particles outside the concentric foliated shells, indicating that if compaction were the cause of microfoliation such compaction must have been anisotropic. Oriented thin sections show that microfoliation is about horizontal in the outcrop, and one might logically consider vertical compaction of the till adequate to account for the anisotropy observed.

Augen structures developed around sand grains have already been described. The felty textural corners of the augen suggest regions more or less protected by the buttressing effect of augen cores. Between the felty textured corners and the large core grains is the typical zone of concentric microfoliation. Apparently these large grains have opposed crowding by the matrix in all directions. Close to the core grains, therefore, compaction has been nearly isotropic; further away, however, highly anisotropic compaction appears to have prevailed.

The following observations are considered most significant in connection with the origin of the microfoliation:

1.—With the possible exception of calcite, there is no evidence of recrystallization or granulation and streaking out of silt grains. It is possible that silt flakes have undergone some static recrystallization, but the initial orientation of particles appears to have survived any recrystallization.

2.—The till lacks certain bedded characteristics such as lenses, layers, and other features of sorting.

3.—Orientation of smaller particles is apparently related to the shape of adjacent larger particles. This control has been referred to as the buttress effect. Though perhaps most striking where the silty matrix is in contact with large fragments, it is, nevertheless, present where

the silt flakes are in contact with silt grains. Generally, silt flakes pack tangentially about each silt grain. Because highly elongate silt grains abound in the finer fractions, most silt flakes depart from parallelism only by a small angle. Where larger elongate fragments are present, they too parallel the dimensional orientation of the silt flakes and grains.

4.—Oriented thin sections indicate that microfoliation has formed roughly horizontally.

It is tentatively concluded that the microfoliation owes its origin chiefly to rotation and packing due to intergranular movement in the till. This process was greatly facilitated by the presence of interstitial water in the till.

Ice load may have acted statically to reduce water content and porosity of the till. It may have acted dynamically causing tamping, effective to shallow depths in the till. Such action would be expected of an ice sheet moving over irregular ground where continued redistribution of internal stresses would be required. Either statically or dynamically the load seems adequate to cause considerable compaction and, therfore, intergranular rotation.

The till probably was deformed also by the spreading or smearing action of the ice which deposited it. This would have been a most effective cause of grain rotation and dimensional parallelism, thus forming a sub-horizontal microfoliation. As successive layers of till accumulated to build up a till sheet, each recorded its own deformation pattern.

Intergranular movement, regardless of its origin, caused silt flakes to mold against the tiny rigid silt grains. It also caused the silt flakes and tiny elongate silt grains to mold against the larger buttressing sand grains. The marked difference in perfection of microfoliation of the silty and sandy tills is due primarily, perhaps, to two factors: (1) the total content of silt flakes in the sandy till is substantially lower than that of the silty till, and (2) the presence of many sand particles is a disturbing factor in the formation of a well-developed microfoliation.

A plastic deformation or kneading action of the till is believed chiefly responsible for the microfoliation. Interstitial water is believed to have aided this action.

ORIGIN OF VEINS

Veins which appear to represent sharp flexures in the microfoliation of the till matrix have been described. The clearest examples appear as thin zones of drag steeply inclined to microfoliation. The trend of silt flakes can be observed to twist in S-pattern upon crossing the vein (fig. 7). In some instances the highly elongate silt grains (0.01×0.05 mm) can be seen to form exactly the same S-shaped pattern across the vein. Vein walls are not sharp, and mineral orientation within the vein is oblique to the walls. This is strongly indicative that a shear type of displacement has flexed the microfoliation of the till.

In many instances the flexed layers cannot be traced uninterruptedly across the veins. Orientation is highly perfect within the veins and some flexing of microfoliation can be observed on either wall. In these examples orientation within the veins is about parallel to vein trend. This is true of elongate silt grains as well as silt flakes. Such veins appear to have formed by flexing and rupture of microfoliation as a result of displacement along shear surfaces. These features resemble fault zones with drag on opposite sides, but in some the drag effect is very difficult to detect.

The branching and braided vein pattern, already mentioned as observed in thin section, can be assumed to represent two sets of shear surfaces developed within the same rock. These two sets commonly intersect at a small to moderate angle and are probably contemporaneous because they appear to mutually cut each other.

Of importance here is the presence, in

one section at least, of abundant microfaults more or less parallel to vein sets. Displacement along these faults must have been relatively large, because small patches with diverging microfoliations are brought into contact with virtually no drag effects. These faults may, in general, post-date the veins, having formed while the matrix was less plastic.

The relations described above fairly well establish the idea that deforming forces have bent or dragged the silt flakes more or less into parallelism with shear surfaces in the till. Evidence opposing the idea that recrystallization has occurred to a marked degree along shear surfaces includes: (1) elongate silt grains which parallel the new structure but which are not recrystallized, and (2) veins with gradational borders due to drag, rather than sharp clean-cut boundaries.

Considerable emphasis is placed here upon grain rotation in zones of shearing. Recrystallization of silt flakes may have occurred to some extent, but the preferred orientation is considered fundamentally due to flake rotation. Perhaps the high perfection of mineral orientation found in the veins, as compared with the adjacent matrix, is due to the intense rotation and intergranular movement within the zones of shear. Such a shearing movement along closely spaced surfaces of slip should be ideal for orienting elongate particles.

Another factor is considered to have played an important role. It seems likely that, when a heterogeneous mixture of silt flakes and silt grains undergoes deformation by shear, the two types of solid phases will tend to segregate, giving rise to a purely mechanical differentiation of the mixture. As segregation continues, the rock aggregate becomes more heterogeneous. Deformation by shear will become more concentrated in those parts of the till which offer least resistance to shear, namely the flake-rich zones. If deformation along these zones continues, the percentage of silt flakes within them may increase at the expense of silt grains. It is not to be implied that the flake-rich zones will be free of silt grains; there may not be a complete separation of the two mineral types. Grain size is also an important factor, and differentiation as to particle size may be as effective as mineral segregation. The highly irregular fashion in which the veins weave between patches of coarser material in some thin sections suggests that the process outlined above may have been operative.

The greater prevalence of veins in the silty tills as compared with the sandy tills may be due to any of several factors: (1) the abundance of silt flakes in the finer tills renders vein structures more easily detected, (2) the silty tills initially possessed a well developed microfoliation which was readily flexed to conform with the superimposed vein structures, and (3) the numerous large fragments in the sandy tills obstructed vein development, compelling shear surfaces to deviate, branch, or assume en echelon arrangement.

The deflection of microfoliation near vein walls indicates that most veining post-dates the microfoliation. The age of those veins which parallel microfoliation, however, is not so readily determined. Some concordant veins appear contemporaneous with associated discordant veins which are clearly younger than microfoliation. Other concordant veins may represent mechanically differentiated material, and may have formed contemporaneously with the microfoliation in localized zones of intense shearing accompanying the smearing action of the ice.

Shear phenomena generating vein structures in glacial tills may be due to a wide variety of processes. The following processes are suggested: (1) horizontal shove of ice against irregular deposits of till, (2) vertical compaction due to load or to sudden and irregular movement of overriding ice mass, (3) differential compaction in heterogeneous deposits, and (4) instability of till near the ice front,

on steep slopes, and around melting blocks of ice.

Suggestions for Future Work

Much further work is needed. Answers to some of the following questions seem pertinent: What are the principal types of vein patterns in tills, and how are they related to each other and to the microfoliation in space and time? What is the regional pattern of these structures, and how are they related to direction of ice movement? How do they vary, for example, throughout the deposits of a single ice lobe? What is the more local pattern of these structures? How do they vary over drumlins and other small glacial features? What changes in microfabrics are encountered with depth in a till section or with tills of different ages in the same section? These are problems we hope to attack and to which we hope others will address themselves in other glaciated areas.

ACKNOWLEDGMENTS

The present study is part of a detailed petrographic investigation of the tills of the northwestern part of the Allegheny Plateau in northeastern Ohio and northwestern Pennsylvania. The field mapping of the glacial deposits in northeastern Ohio by G. W. White and his associates is part of a cooperative investigation of the U. S. Geological Survey (Groundwater Branch) and Ohio Division of Water (White 1951, 1952, 1953a, and 1953b). The investigation of till characters in the Allegheny Plateau has been supported by a National Science Foundation Grant to Professor White.

We are grateful to Professor White for numerous helpful suggestions and for the opportunity to study sections from the till blocks which he collected in the field. We are grateful for the field expenses of one of us (R.F.S.) from the National Science Foundation Grant.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 270–272
DECEMBER, 1955

ARAGONITE NEEDLES SECRETED BY ALGAE AND SOME SEDIMENTARY IMPLICATIONS[1]

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ABSTRACT

A variety of common marine calcareous algae from the tropical and subtropical West Atlantic are shown to be subject to post-mortem disaggregation. The calcareous hard parts of many of these algae, including both green and red forms, consist wholly or partially of aragonite needles. These algally secreted needles are similar in habit and dimensions to sedimentary aragonite needles, all of which have previously been attributed to inorganic, physiochemical precipitation from sea water. In several widely scattered areas, the occurrences of such needle-secreting algae coincide with sediments that contain aragonite needles; this infers a largely algal origin for the sedimentary needles. These algae and associated sediments are not limited to the West Atlantic and probably occur through the tropical seas.

A number of typical warm water calcareous algae seem generally to have escaped notice in bioclastic sedimentary analyses despite the fact that they form sizable populations on or near the bottoms from which studied samples had been taken. In the West Atlantic the unreported algae include species of the genera *Acetabularia*, *Cymopolia*, *Rhipocephalus*, *Udotea* of green, *Padina* of brown, and *Liagora* and *Galaxaura* of red algae. The remains of other algae such as *Acicularia*, *Neomeris* and *Penicillus* have been reported once from Bahama sediments (Illing, 1954) but only in amounts proportionally small when compared with living populations. Most of these algae are known to be weakly calcified (Pia, 1926), and post-mortem disaggregation of these is likely to occur. Have the contributions of these warm water algae to the sedimentary record been very small, or has their subsequent disaggregation prevented recognition of perhaps quite significant contributions?

Comparative studies on the aggregation character, mineralogical composition, crystal habits, and crystal dimensions of algal encrustations were undertaken to investigate the role of these algae in the sedimentary record. The material used for the study was primarily from Bermuda, supplemented by the same and other species from Florida, the Bahamas, and Jamaica. The Bermuda collections included all known species in that area.

The calcifications residual after digestion with 5.3 percent sodium hypochlorite were found to disaggregate into fragments of varying dimensions and configurations, including single crystals. Since *Halimeda* is generally reported from sedimentary analyses (for references to the literature, see Chave, 1954), it is noteworthy that certain species of this genus also disaggregated. In many of the aragonite-secreting algae the calcification consists largely or entirely of acicular crystals. Similar aragonite needles have long been known from calcilutites of certain areas. Since possible contribution of aragonite needles by algae to the sediments was indicated, the problem of the source of aragonite needles in sediments has been reviewed.

Aragonite needles have now been found in the aragonitic calcification of the following algae: *Cympolia barbata;* the species *tuna monile* and *opuntia* of the genus *Halimeda;* the species *capitatus*

[1] Contribution No. 734, California Institute of Technology. Bermuda Biological Station Contribution No. 191.

and *pyriformis* of the genus *Penicillus;* the species *conglutinata, wilsoni cyathiformis* and *flabellum* of the genus *Udotea; Rhipocephalus phoenix;* the species *ceranoides* and *farinosa* of the genus *Liagora;* and the species *obtusata* and *rugosa* of the genus *Galaxaura*. Aragonite needle formation seems thus prevalent in the Codiaceae, and less frequently developed in the Dasycladaceae, Nemalionaceae, and Chaetangiaceae. Single crystal release through sodium hypochlorite treatment is a small part of the total calcium carbonate in most species. It is more extensive in *Halimeda tuna* and the *Udoteas* and highest in *Rhipocephalus phoenix*. In calcification aggregates the needles are usually arranged to form interlacing mats. Crystal dimensions of the needles range from two to nine microns in length and about one-half micron in diameter.

The fragile character of the residual aggregations suggests that more advanced disaggregation and hence a greater supply of single needles should result from the more rigorous treatment to which the bacterially freed calcifications are subjected in nature. Such processes are wave action, physical disturbances by sediment plowing and digging biota, and, above all, the intestinal pressures exerted in sediment ingestions by the abundant holothurians.

If these algae are a source of sedimentary aragonite needles, then throughout their geographic range living sites and depositional grounds of the two should be coextensive in quiet water habitats. Quiet water samples were collected from areas without previously reported needle records. These came from bottoms populated abundantly by species of *Udotea, Penicillus* and *Halimeda* from the lagoon inside West Reef and inside Castle Harbor, Bermuda, and from the lagoon inside the fringing reef at Ocho Rios, Jamaica. The calcilutite fractions were found to contain aragonite needles while the coarser fractions contained minute needle aggregates.

In the Florida Key area the writer found the greatest density of species of *Penicillus, Udotea, Rhipocephalus, Halimeda, Liagora,* and *Galaxaura* in the area between the outer reefs and the Keys. This coincides with the greatest abundance of aragonite needles recently reported by Ginsburg (1953) from sediments along a traverse from outside the outer reefs past the Keys into Florida bay. The Bahamas are the classic site of aragonite needles (Cloud and Barnes, 1948). A survey by the writer of the calcareous algae around Andros Island and several Cays near Eleuthera again showed large populations of the same algae noted in Florida with one exception, namely that *Rhipocephalus phoenix* with the highest needle release is here a more abundant element of the algal populations. Aragonite needles found in the sediments and needles isolated from algae from the Bahamas were compared. Crystal habits and dimensions are very similar.

Aside from Bahama and Florida, literature records of sedimentary aragonite needles include the Tortugas off Florida (Vaughan, 1924) and Maiao in the Society Islands, South Pacific (Williams, 1933). Vaughan (1917), the first to call attention to their occurrence in Florida-Bahama calcilutites, attributed them to inorganic physio-chemical precipitation from sea water. Following artificial laboratory precipitations by Gee (1932) of similar aragonite needles by passing carbon dioxide-free air through Tortugas sea water, Vaughan's interpretation became widely accepted.

Sedimentary needles and algally-secreted needles have an overlapping size range. The dimensions of artificial precipitates reported by Revelle (1932) average somewhat less than the natural types, but the controlling conditions of the artificial growth are not accurately known and the size differences are therefore not considered significant.

The lack of corroborating evidence at Bermuda, Jamaica, and Florida speak against a physiochemical precipitation.

If inorganic precipitation were involved, the Florida Bay area, an ideal insulation basin, should then have the greatest needle abundance, but as Ginsburg (1953) has already pointed out, this is not the case. Only in the Bahamas, where some definite precipitates are known to accompany the needle occurrences (Illing, 1954), is there any legitimate reason to attribute at least some needles to chemical precipitation.

The discovery of algally-secreted needles establishes an endemic biogenic source for aragonite needles in sediments for the first time. The concordant distribution and abundance relations between the critical algae and sedimentary needle occurrences in the examples cited answers in large part the question raised here initially. The post-mortem role of the calcifications of many algae which have not been reported or reported only in small amounts in bioclastic debris, is actually important in the sedimentary record. Single needles and calcification fragments can now be shown to be deposited in the clay to sand size fraction.

Representatives of algal genera, with aragonite-secreting species in the west Atlantic, are also distributed widely in subtropical and tropical seas elsewhere. Cursory examination of congeneric species showed aragonite needles in *Udotea orientalis* from the Philippines, *Udotea argentea* from New Caledonia, *Udotea* (*Flabellaria*) *desfontainii* from Tripoli in the Mediterranean, and from several unidentified species of *Halimeda* from Kayangle atoll, Palau. Sediment samples collected by the writer in the Kayangle lagoon contain aragonite needles. Therefore, wherever aragonite needle-secreting algae occur within equatorial shoal waters, bounded by the 15°C isotherms for the coldest month of the year, quiet water sediments should contain aragonite needles. Another implication is that fossil calcilutites attributed to physiochemical precipitation or mechanically reduced skeletal carbonates may have been partially or largely derived from algally-secreted aragonite needles from ancestral algae.

Acknowledgment is made to Dr. A. Bernatowicz for identification of Bermuda algae, Dr. E. Y. Dawson, for specimens and literature data, and Dr. P. H. Monaghan from Humble Oil and Refining Company for needle bearing bottom samples from the Bahamas. Research was supported by a grant from the California Research Corporation.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 273–281
FIGS. 1–6, DECEMBER, 1955

INVERSE GRADED BEDDING IN PRIMARY GYPSUM OF CHEMICAL DEPOSITION

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ABSTRACT

The Gypsum formation of the Sulphur series of Sicily shows thick gypsum beds, mostly made up of basal zones of primary gypsum with rhythmic structure and of thicker upper zones of secondary gypsum. The latter is characterized by swelling structures due to transformation from anhydrite.

The rhythmic primary gypsum is bedded in two to three mm thick laminae, which present a structure of inverse graded crystalline mosaic with the finer grain sizes at the base and the bigger ones at the top.

Some slightly reworked types of primary gypsum show loss of the grading and uniform grain size. Some rhythmites show a grading from finer to bigger sizes, ending in the deposition of anhydrite crystals which have been transformed to gypsum during the deposition of the following lamina, thus deforming it.

The inverse size grading is referred to a seasonal concentration increase by evaporation, possibly together with an average temperature increase. The return to the initial sizes at the base of each lamina is attributed to a rainy, perhaps cold season, which interrupts the evaporation and consequently the chemical deposition.

STRATIGRAPHIC POSITION OF THE PRIMARY GYPSUM IN SICILY AND ITS SIGNIFICANCE

The Upper Miocene Sulphur series of Sicily has been described in previous papers (Ogniben, 1953; 1954a; 1954b). From top to bottom it is: (1) Trubi formation (Globigerina marl and marly limestone); (2) Gypsum formation (interbedded gypsum, marl, and clay); (3) Basal limestone formation (evaporitic limestone interbedded with minor marl); (4) Tripoli formation (interbedded diatomite and diatomitic marl). It includes other minor more discontinuous members among which are the well known sulphur sedimentary deposits interbedded between Basal limestone and Gypsum formations and important halite and potassium-magnesium salt deposits within the Gypsum formation. It is a typical "arid restricted basin" association, related to a phase of regression and separation of the Mediterranean area from the oceans.

In marginal areas of the "arid restricted basin" the Gypsum formation shows the "sulphiferous facies" with prevalence of gypsum and minor interbedded marls and clays. It reaches 100 meters maximum total thickness and contains the sulphur deposits at its base. From Mt. Etna to Sciacca, in a median area of the basin, the "saliferous facies" which attains maximum thickness of about 1000 meters, with very abundant marls and clays and interbedded saline deposits, is shown.

Gypsum occurs in beds from one to some tens of meters thick which are mostly made up of secondary gypsum by transformation from anhydrite, and by a thin basal zone of primary gypsum of chemical deposition (fig. 1). The latter is a dense microcrystalline white-grayish rhythmic rock, or rhythmite (Sander, 1936), of waxy appearance, distinctly divided into thin laminae, and often fissile. Its local name is balatino.

The selenitic secondary gypsum of the "sulphiferous facies" has already been described (Ogniben, 1954c). It makes up the greatest part of the thick gypsum beds as selenite in swallow tail (100) twins a few centimeters long with a

FIG. 1.—Thick beds of secondary selenitic gypsum divided by interbedded marl. Note the thin zone of primary gypsum at the base of the upper bed. Grottacalda, Enna, Sicily.

preferred orientation according to the Mottura's Rule, i.e. with the twinning plane and the c axis perpendicular or subperpendicular to the bedding plane, and with a constant polarity of the twins concave angle toward the top of the beds, and of the apex toward the bottom. Swelling structures of the upper surface of the beds and deformation of the overlying marls make the transformation from anhydrite evident. This event seems to have been paradiagenetic as is indicated also by the present study.

The alabastrine secondary gypsum of the "saliferous facies" is a white saccharoidal rock with irregular knotlike swelling structures, and seems to have originated by recent transformation of anhydrite caused by the approach of the external erosion surface.

In both facies, at the base of the formation some beds can be entirely made up by primary rhythmic gypsum, and at the top some beds can be wholly made of secondary gypsum; but in most beds the typical association is a thin basal zone of primary gypsum with a much thicker upper part of secondary gypsum (fig. 2). The sequence, marl—primary rhythmic gypsum—secondary gypsum—marl, is thus polar from bottom to top, always repeating itself in the same order.

This cyclical sequence bears a precise significance. The interbedded marls, so common in evaporitic formations, were originated by periods of terrigenous supply, and therefore of strong water inflow, which interrupted or overshadowed the chemical deposition. When the latter started again, gypsum, now visible as rhythmite, always precipitated first, after which deposition of anhydrite, now visible as secondary gypsum, took place.

The next following phase of terrigenous supply caused dilution of the basin water, and the successive chemical deposition took place as gypsum again, thence passing to anhydrite, and so on.

Transition from gypsum to anhydrite in calcium sulphate deposition by evaporation is caused by increase of concentration and temperature (Posnjak, 1940). Deposition of gypsum from sea water at 30° takes place when concentration has reached 3.35 times the normal salinity, and deposition of anhydrite takes place after having reached 4.8 times the normal salinity. These conditions are not greatly modified at temperatures even 10°–15° lower. At 42° anhydrite always will be deposited whatever the type of calcium sulfate solution may be.

In geological environments variation of concentration must be more determinant than that of temperature, since average temperatures much over the above mentioned 30° could have hardly lasted for such a long time as that required by the formation of the gypsum layers. A slow salinity variation is easily understood if a balance between inflow of water and loss by evaporation is admitted. In this way the water concentration can be maintained for a long time in the field of less solubility of gypsum, very slowly increasing until it reaches the field of less solubility of anhydrite, with still longer permanence in this field.

The possibility of such an equilibrium must be accepted since it is documented by its products. Only a continuous inflow of sea water can have carried to the various basins the enormous quantities of evaporitic minerals we find to-day in the corresponding formations. So only a close

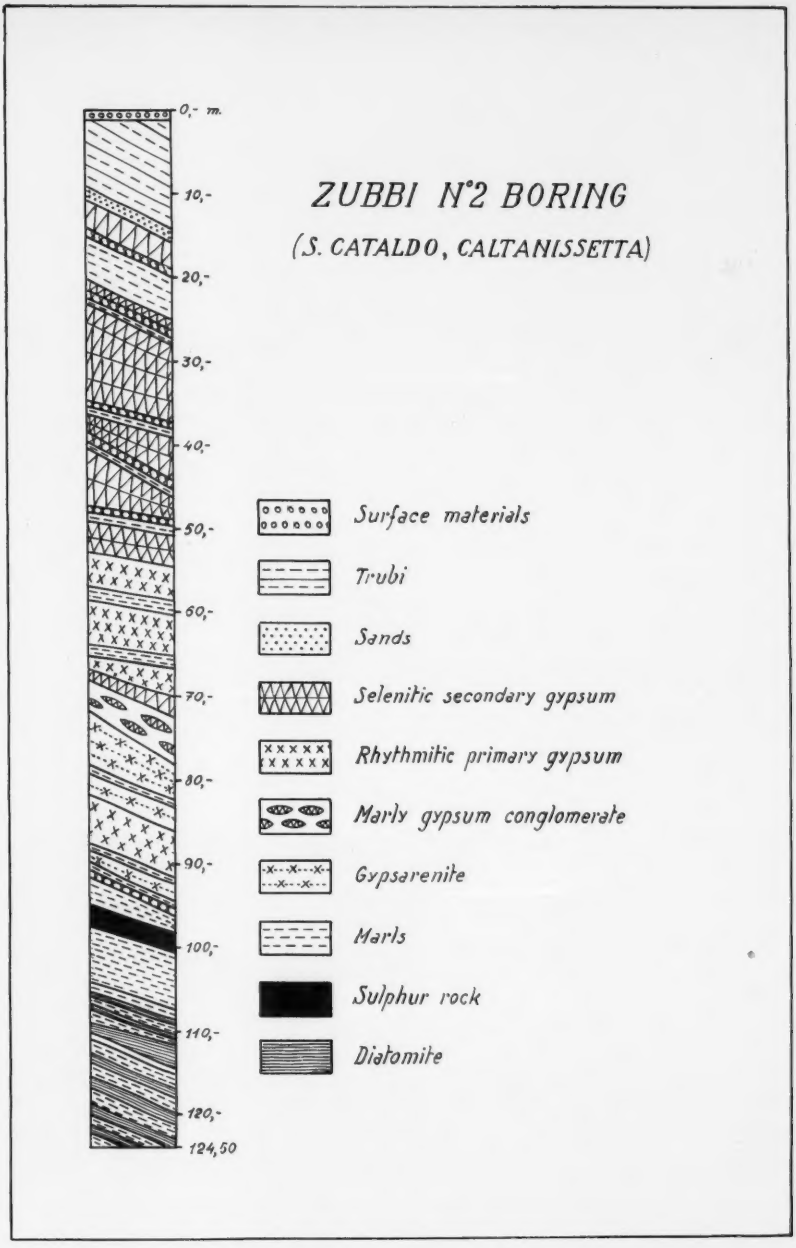

FIG. 2—Typical sequence of primary and secondary gypsum beds interbedded with marl and clastic gypsum. The Gypsum formation passes upward into the Trubi, downward into the Tripoli formation (diatomite). The Basal limestone formation is lacking. S. Cataldo, Caltanissetta, Sicily.

correspondence between inflow and loss by evaporation could have maintained the water concentration of the various basins in the deposition field of a single mineral for such a long time, without allowing the successive precipitation of the whole sequence of evaporation minerals in a short time.

The chance of such a nice balance is all the more evident because the inflow of water is originated, and thus ruled, by the loss by evaporation. Since during the the gypsum deposition there was no deposition of all other salts carried by the water flowing into the basin, a slow increase of salinity took place. After a while, this led the concentration into the field of anhydrite deposition which lasted until the next period of terrigenous supply and of water dilution. This explains the sequence of terrigenous marl, primary gypsum (rhythmite), and anhydrite (secondary gypsum).

The absence of swelling structures shows that the rhythmite was directly deposited as gypsum rather than as anhydrite. Thus, the investigation of an originary structure of chemical deposition, not yet fully known as such, is granted, since the evaporites thus far investigated are wholly recrystallized like the saline deposits, or were subjected to transformations and to very strong tectonic disturbances like the Permian evaporites of the saline domes of the United States and of Germany. Udden (1924) describes an anhydrite rhythmite of the Castile formation of Texas, probably of primary deposition, which resembles the gypsum rhythmite studied here, but he does not fully analyze its microstructure.

MICROSTRUCTURE OF THE RHYTHMIC PRIMARY GYPSUM

Under the microscope the gypsum shows bedding laminae one to five mm, but mostly two to three mm thick. They are frequently made evident by very thin intercalations of marly pelite, but especially by the inverse grading of the gypsum grains. These form a polygonal mosaic with euhedral tendency, showing a grain size of 0.01 mm at the base of the laminae, gradually increasing to average sizes of 0.15–0.2 mm at the top (fig. 3). Common are rhomboidal sections of prismatic grains and less common lamellar sections of tabular ones with the longest diameter lying in the bedding plane. However, nearly isodiametric irregularly polygonal grains are most abundant.

The grains show a more or less strong preferred orientation, easily observed with the gypsum plate, generally having

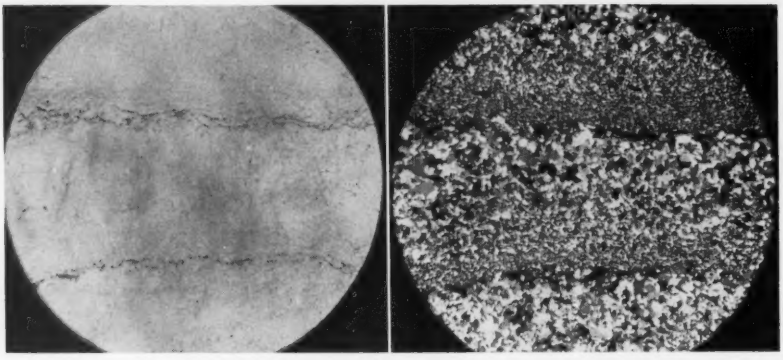

FIG. 3.—Inverse graded bedding in primary gypsum laminae separated by thin pelite streaks. Parallel and crossed nicols, ×10.

γ^1 perpendicular to the bedding plane, but in some specimens γ^1 is parallel to the bedding plane. Since there are no traces of recrystallization, the preferred orientation must be ascribed to a mechanical effect of elongated or flat grains settling down with their longest diameter parallel to the deposition surface. The prevailing isodiametric polygonal grains, also following the preferred orientation rule, must therefore be derived from original elongated forms, later blunted and made isodiametric by solution phenomena due to rock compaction. This manner of compaction by solution is typical for gypsum rocks, and can be seen very well in the gypsarenites of the Sulphur series containing microfossils and other grains less soluble than gypsum.

The marly pelite of the thin intercalations between the graded gypsum laminae or between single gypsum grains results in carbonate grains generally of a size about 0.001 mm, and in argillaceous matter of still finer size. It is, therefore, normal marl like that interbedded between the big gypsum layers. Very small foraminifera, *Globigerina* and *Bulimina*, with diameters about 0.05 mm, are sometimes associated with it.

Another widespread accessory component is chalcedonic silica in either simple fibro-radiating aggregates or showing several aggregation centers with diameters up to 0.1–0.2 mm (fig. 4). They evidently are authigenic by replacement of gypsum caused by siliceous solution coming from neighboring formations like the underlying Tripoli formation. The latter is essentially composed of opaline silica which is supposed to be the original form of most chalcedonic silica (Pettijohn, 1949).

The chalcedonic spherulites often clearly show their aggregation centers lying in a former intergranular border between gypsum grains, sometimes with small grains of quartz or of another silica form in the center.

Rare accessory components of these gypsum rhythmites are very small granules of pyrite showing diameters from 0.01 to 0.05 mm.

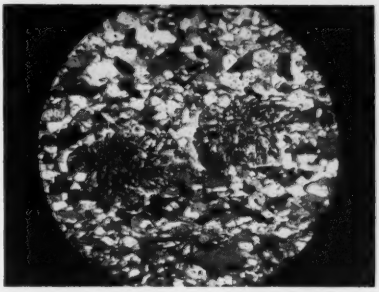

FIG. 4.—Resedimented primary gypsum, with authigenic chalcedonic aggregates. Crossed nicols, ×27.

RESEDIMENTED PRIMARY GYPSUM

In the strata of rhythmic gypsum nonrhythmic zones, sometimes extending over the entire stratum, can be observed. Under the microscope their chief characteristics are absence of grading and uniform grain size, varying in different strata from 0.02 mm to 0.05–0.1 mm (fig. 4). There is a greater amount of marly pelite in the non-rhythmic zones than in the rhythmic layers, but it is scattered among the grains instead of being concentrated in thin streaks between the laminae. The bedding plane is evident by the parallelism of the elongated or flat grains.

Detrital minerals, which are rare in the rhythmic gypsum, are frequent. Among them are angular fragments of calcareous aggregates, detrital quartz, detrital rounded glauconite in sizes up to 0.05 mm, and lamellae of brown clay minerals of medium birefringence or of greenish chloritic minerals of very low birefringence. Common are *Globigerina* and *Bulimina* of small size (0.05–0.1 mm) and authigenic fibro-radiating aggregates of chalcedony (fig. 4) often originating from central fragments of detrital silica, analogous to those of the rhythmites.

The reworking significance of this

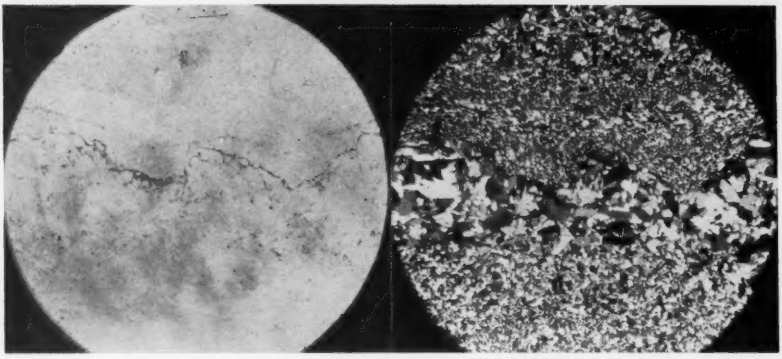

FIG. 5.—Mixed primary-secondary gypsum rhythmites. Geopetal structures of swelling at the upper surface of the laminae, and of filling by small size gypsum in the depressions. Parallel and crossed nicols, ×10.

structure is made clear first by the disappearance of the rhythmic grading. In addition, there are the frequency of foraminifera, the occurrence of noticeable amounts of psammitic detrital materials, and of terrigenous pelite in larger amount than in the rhythmic gypsum. The study of other rocks of the Gypsum formation shows that organic remains associated with gypsum always bear a detrital significance, as does the rounded glauconite in the whole Sulphur series.

The homogenous grain size is due to sorting by transportation. There are resedimented primary gypsum layers with a 0.02 mm grain size, evidently originated by the accumulation of the small basal grains of the rhythmic laminae. More often the primary resedimented gypsum rocks show a 0.05–0.1 mm grain size, clearly caused by accumulation of the top gypsum of the rhythmic laminae.

In resedimented primary gypsum there is no readily visible preferred orientation as in the rhythmites. Therefore, it has been destroyed by the reworking and must be considered a characteristic of the very first sedimentation process.

RHYTHMITES WITH ASSOCIATED PRIMARY AND SECONDARY GYPSUM

A third structural type is megascopically visible by the occurrence of rows of gypsum crystals one mm or more in size between the dense rhythmic laminae. This type is widespread in the Gypsum formation, and it can be found in layers up to several meters thick, all or partly substituting for the normal rhythmic gypsum.

Under the microscope isolated crystals or groups of crystals, averaging 1–2 mm in size, can be observed at the top of the inverse graded laminae, while all other normal or accessory components of the rock are like those of the normal rhythmites. The major size crystals more or less continuously follow the top border of the laminae in form of upward rising structures. The corresponding depressions between them are marked by the thin interbedded pelitic streaks. A thin basal zone of the smallest size gypsum of each overlying lamina exactly follows the undulated surface of each underlying lamina, thus showing that it shared in the deformation. Small size gypsum also fills the depressions of this basal zone with a very clear geopetal sedimentation picture (fig. 5), thus allowing the following small size gypsum to be deposited on a flat surface and to continue upward in the normal inverse graded lamina.

The upper surface swellings of each underlying lamina seem, therefore, to have formed during the deposition of the

first small size gypsum of each overlying lamina in such a manner that a part of the gypsum was deformed, a part filled the resulting depressions, while the remaining portion of the lamina did not undergo any deformation.

Many big gypsum crystals are variously oriented (100) twins and many of them follow the previously mentioned Mottura's Rule, i.e. they are subperpendicular to the bedding and present the concave angle upward and the apex downward. Their length sometimes exceeds the thickness of the containing lamina, stretching out into the overlying and sometimes into the underlying lamina, deforming the small size gypsum sediment.

The position of these crystals, perpendicular to the bedding, is sufficient proof of their epigenetic origin. In addition, at their borders a crystalloblastic cribrose structure is to be observed which is indicative of their growth within the sediment. Often seriated ruptures perpendicular to the crystal elongation are also observed, with small displacement of the single pieces and resulting formation of a superindividual (fig. 6).

This crystalloclastesis, together with the deformation of the embedding sediment, the elongation of the crystal perpendicular to the bedding, and the crystalloblastic structures, clearly shows that a crystal neoformation took place with mechanical strains due to volume increase, i.e. to the transformation from anhydrite.

A gypsum deposition like that of the normal rhythmic layers must, therefore, have taken place ending with deposition of some anhydrite grains of bigger size than the gypsum ones on each lamina top. During the successive deposition of the small size gypsum belonging to the overlying lamina, the anhydrite grains underwent a transformation into big size gypsum, swelling and thus partly deforming the embedding sediment.

These mixed primary-secondary gypsum rhythmites often show a trend toward anhedral forms and a size increase of the primary gypsum grains, i.e. a trend toward the "Sammelkristallisation" of the German authors.

The significance of the mixed primary-secondary gypsum rhythmic deposition is that of a cyclical oscillation about the anhydrite-gypsum transition point. The phenomenon could have been a temperature oscillation, but more likely consisted of a concentration oscillation. The normal rhythmites, therefore, represent oscillations (graded bedding!) within the field of less solubility of gypsum with slow gradual increase of salinity until it reaches the field of anhydrite deposition (now represented by the thick layers of secondary gypsum); i.e. with slow displacement of concentration in a nice oscillating equilibrium between water evaporation and inflow from outside of the basin. In a like manner the mixed primary-secondary gypsum demonstrates a long salinity oscillation about

FIG. 6.—Cataclastic twinned superindividual, showing elongation perpendicular to the bedding (Mottura's Rule), and crystalloblastic structure at its borders. Crossed nicols, ×10.

the gypsum-anhydrite transition point. This is a particular case, wherein the oscillating concentration remained predominantly either in the gypsum stability field, or in the anhydrite one.

SIGNIFICANCE OF GRADED BEDDING

Graded bedding has been known for a long time, but it has found ample treatment only in two classical papers, one by Bailey (1930) who stressed its connection with the geosynclinal detrital deposits and the other by Kuenen and Migliorini (1950) who related it to redeposition of detrital sediments by turbidity currents.

No descriptions have been found of graded bedding of sediments other than detrital. Inverse graded bedding has been referred to by Kuenen and Migliorini (1950), always in relation to detrital materials caused by variations in transport competency.

In the Gypsum formation of Sicily there are also detrital gypsum sediments, originated by reworking of the chemical deposits, but they are typical littoral formations, lenticular in form and with bedding of the current type. True psammitic ("gypsarenites") and psephitic gypsum rocks of this kind are widespread. What can be inferred on the geological environment of the Sicilian evaporites does not agree with the various possibilities of detrital graded bedding according to Kuenen and Migliorini (1950). The evaporitic basins were small and irregular, receiving very little terrigenous supply, and showing a tendency to become dry and miss many members of the deposition sequence.

The mixed primary-secondary gypsum rhythmites seem to demonstrate that the grain size increase of the sediments was connected with a concentration increase of the basin water since the deposition of the big size gypsum crystals ended in the deposition of anhydrite crystals. Afterwards, basin water dilution again caused deposition of very small gypsum crystals and at the same time it caused transformation of anhydrite into gypsum, thus straining the newly formed sediment.

The parallel change of the crystalline size of gypsum and of the saline concentration is very interesting, because it would be possible to control it experimentally. A relationship between grain size and temperature could not have been expressed so simply since it ought to have recorded strong daily variations, not only seasonal ones. However, it is possible that an average temperature effect has contributed to the grain size increase.

The variation of concentration expressed in the graded bedding, and thus also the laminae deposition rhythm, seems to have been nothing else than seasonal. The chemical deposition would correspond to an arid and eventually warm season; the interruption of deposition, the small terrigenous deposit of the thin pelitic streaks, and the dilution of the basin water would correspond to a rainy and eventually a cold season. No independent inflow of sea water is possible as a cause of the deposition rhythm since it was controlled by water evaporation, and this in turn by the seasons.

The passages between the evaporitic basin and the oceans may have been more or less wide. The only necessary condition was a restricted circulation which permitted inflow of normal sea water at the surface to balance the loss by evaporation and prevented outflow of concentrated water in depth. In this way a slow concentration in the whole basin was inevitable, and was only interrupted by major geological events.

The present study thus explains the depositional environment of the Gypsum formation of Sicily as a region of basins of little depth. The rhythmic sedimentation structure was generally preserved but sometimes subject to reworking. The average environmental temperatures were about the same as Posnjak's (1938, 1940. i.e. about 30°, with ample oscillations possible.

According to all the considerations

mentioned above, the single laminae seem to correspond to annual deposits, i.e. varves, like all the mm-rhythmites (Sander, 1936, with the previous literature). An average thickness of two to three mm can be calculated for each lamina, from about two mm (2.2–2.3 mm) for normal rhythmites, to about three mm for mixed primary-secondary gypsum rhythmites.

For the thin basal primary gypsum zones, 20–50 cm, of the main gypsum beds, a depositional time from 100 to 200 years may be therefore calculated. For the bulky beds of independent primary gypsum, which often can be seen at the base of the Gypsum formation, a maximum thickness up to 14.5 m has been measured. Its depositional time, therefore, may have lasted about 7000 years.

The arrangement of primary and secondary gypsum in thick layers interbedded with marl layers was probably controlled by tectonic phenomena related to the rhythm of subsidence.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 282–284
FIGS. 1–2, DECEMBER, 1955

FUCOIDAL MARKINGS IN THE SWAN PEAK FORMATION, SOUTHEASTERN IDAHO

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ABSTRACT

Physical features of the fucoidal markings in the Swan Peak formation suggest a mode of origin involving incorporation of coarse sand particles and organic fragments in a gelatinous organism plus the influence of the chemical by-products of the decomposition of the organism on the cementation process during diagenesis.

Among the most striking features of the Swan Peak formation in southeastern Idaho are the abundant fucoidal markings on bedding planes in the quartzitic sandstone members of the formation. Although these markings are scattered throughout the formation they are most common within the dark reddish-brown middle member. Several interesting details of these markings throw some light on their mode of origin.

Fucoidal markings have been discussed in geologic literature for a long time. (Newberry, 1885). They were first noted by Locke in Ohio in 1838 and were named *Fucoides biloba* by Vanuxem in 1842. Similar markings were called *Cruziana* by D'Orbigny in 1842, *Fraena* by Roualt in 1850 and *Rusophycus* by Hall in 1852. All these men regarded them as impressions of seaweeds. This contention was reaffirmed by Saporta (1884) although he erroneously referred them to the genus *Bilobites*. Similar markings were considered by Dawson (1864), Hughes (1884), Nathorst (1883) and James (1884) to be the tracks of various organisms or in some cases to be of inorganic origin. James (1884) objected to the promiscuous application of the term fucoid and recommended that it be restricted to its original sense, i.e., to the fossilized remains of seaweed. Similar features of indeterminate origin he believed should be called fucoidal markings. The term fucoidal marking used herein is intended simply as a form designator implying a physical resemblance to, but not a genetic relationship with, the modern seaweed, *Fucus*.

The fucoidal markings of the Swan Peak formation are irregular, cylindrical, raised welts on the bedding planes of the quartzitic sandstone (fig. 1). The individual welts vary in length from a fraction of an inch to eight inches and in diameter from approximately $\frac{1}{8}$ of an inch to $\frac{3}{8}$ of an inch. Some of the ridges radiate outward from a central node and others branch dichotomously from single stems with no apparent central node. Complex intertwining of welts is common. The distal terminations are acuminate. The surfaces of the individual welts, although somewhat irregular, have no systematic transverse or longitudinal markings. In section, parallel to the bedding planes,

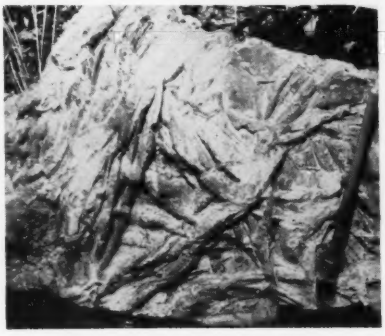

FIG. 1.—Fucoidal markings in the Swan Peak formation.

many of the welts are found to contain concentrations of relatively coarse organic particles, ostracods and trilobite fragments, and a higher percentage of large sized quartz grains than the enclosing ground mass (fig. 2). In some places the trilobite fragments penetrate one or both walls of the welt (see fig. 2).

The various hypotheses of origin for the many features of sufficient similarity to be referred to as fucoids or fucoidal markings may be summarized as follows:

1. Fossilized remains of various organisms.
2. Impressions of various organisms.
3. Back-filled burrows or borings of small annelids, mollusks or crustaceans.
4. Burrows or borings of small annelids, mollusks or crustaceans which have been filled by later collapse of overlying material.
5. In-filled tracks or trails of small organisms.
6. In-filled mud cracks.

It is believed that the observed features of the Swan Peak fucoidal markings militate against any of the above hypotheses of origin for these particular features for the following reasons:

1. There are no observable cellular microstructures to suggest that these markings are fossilized remains of organisms nor does it seem likely that coarse fragments of the type shown in figure 2 would become incorporated within the body of any organism which possessed sufficient structural rigidity to allow subsequent fossilization.
2. If these features were casts of impressions on bedding surfaces they would necessarily be underside markings as pointed out by Grabeau (1913) whereas they are topside positive markings.
3. The size of the transverse fragments within the markings argues strongly against their origin as back-filled borings.
4. The fact that transverse fragments within the markings in some cases penetrate both walls, and the complex intertwining of the welts makes their origin by filling of borings by later collapse of overlying material improbable.
5. In-filled tracks of trails would necessarily be underside features rather than topside features.
6. In-filled mud cracks would not show the complex intertwining pattern of these markings.

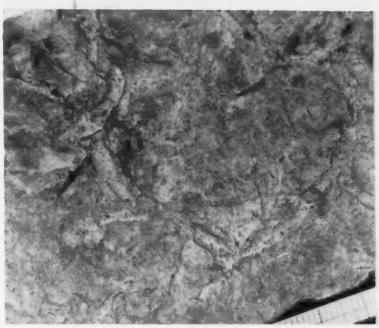

FIG. 2.—Section through fucoidal markings parallel to bedding showing organic particles within the markings.

A possible mode of origin for these particular features is suggested by Raymond's (1922) description of the preservation of jelly fish. He observed partially dehydrated, stranded jelly fish to which sand grains had adhered. The gelatinous material cemented the grains of sand together and the mass of the sand grains prevented excessive shrinkage of the jelly fish. The sand varied from fine to coarse; in one case a flat pebble 14 mm in diameter was incorporated.

The fucoidal markings in the Swan Peak formation may have had a similar history. Given an original organism, either plant or animal, of proper configuration, coarse sand and organic fragments might subsequently be incorporated. The chemical by-products of decomposition of the organism might influence the cementation process during diagenesis, to make them stand out as separate bodies.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 285–292
DECEMBER, 1955

PHI-MILLIMETER CONVERSION TABLE[1]

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ABSTRACT

A phi-millimeter conversion table, computed with the use of seven-place logarithms, is presented. This table permits greater accuracy and is less tedious to use than previous methods of conversion.

INTRODUCTION

The phi symbol, ϕ, as originally adopted by Krumbein (1934; 1936b), is used to denote a grade scale in which all divisions are equal in range. This adapts the grade scale for plotting the data of mechanical analyses on arithmetic graph paper, thereby producing increased symmetry of the frequency curve and making possible direct arithmetic interpolation between phi grain diameters on the curve. To calculate many of the measures used in mechanical analyses, such as median diameter, quartiles, percentiles, and coefficients of sorting, skewness, and kurtosis, the phi units must be converted to millimeter sizes for use in the formulas involved or for easier comprehension of values. The slide rule or logarithms facilitate the algebraic computations in phi-millimeter conversions, but both processes are more or less tedious. Conversion charts now in use include those of Krumbein (1936a), Truesdell and Varnes (1950), and Inman (1952). Although these charts are sufficiently accurate for many uses, they require eye-straining observation and interpolations which result in only approximate values for intermediate grain-sizes.

The following table has proved very useful in conversions involved in mechanical analyses of sediments made as part of ground-water studies by the Navajo Project, U. S. Geological Survey. The table was computed with the use of seven-place logarithms (Hutton, 1830); hence it permits more accurate, faster, and easier conversions than most charts now available. Few groups of workers may require the complete table to cover the size-ranges their work involves, but the limits of the table were designed to encompass the major grain-sizes commonly employed by workers in various fields of analysis. Likewise, the figures are computed to three to five decimals to satisfy the requirements of those who desire that degree of accuracy.

Grain diameters smaller than one millimeter are represented by a positive phi value and are shown in the second column of the table; diameters larger than one millimeter are represented by a negative phi value and are shown in the third column.

ACKNOWLEDGMENTS

The author is indebted to Dr. E. B. Mayo of the University of Arizona for his helpful suggestions and encouragement in initiating computation of the table, and to Prof. D. L. Bryant of the University of Arizona for his sponsorship of this article.

[1] Publication authorized by The Director, U. S. Geological Survey.

Phi-Millimeter Conversion Table

ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.
0.00	1.0000	1.0000	0.50	0.7071	1.4142	1.00	0.5000	2.0000
01	0.9931	0070	51	7022	4241	01	4965	0139
02	9862	0140	52	6974	4340	02	4931	0279
03	9794	0210	53	6926	4439	03	4897	0420
04	9718	0285	54	6877	4540	04	4863	0562
05	9659	0355	55	6830	4641	05	4841	0705
06	9593	0425	56	6783	4743	06	4796	0849
07	9526	0498	57	6736	4845	07	4763	0994
08	9461	0570	58	6690	4948	08	4730	1140
09	9395	0644	59	6643	5052	09	4697	1287
0.10	9330	0718	0.60	6598	5157	1.10	4665	1435
11	9266	0792	61	6552	5263	11	4633	1585
12	9202	0867	62	6507	5369	12	4601	1735
13	9138	0943	63	6462	5476	13	4569	1886
14	9075	1019	64	6417	5583	14	4538	2038
15	9013	1096	65	6373	5692	15	4506	2191
16	8950	1173	66	6329	5801	16	4475	2346
17	8890	1251	67	6285	5911	17	4444	2501
18	8827	1329	68	6242	6021	18	4414	2658
19	8766	1408	69	6199	6133	19	4383	2815
0.20	8705	1487	0.70	6156	6245	1.20	4353	2974
21	8645	1567	71	6113	6358	21	4323	3134
22	8586	1647	72	6071	6472	22	4293	3295
23	8526	1728	73	6029	6586	23	4263	3457
24	8468	1810	74	5987	6702	24	4234	3620
25	8409	1892	75	5946	6818	25	4204	3784
26	8351	1975	76	5905	6935	26	4175	3950
27	8293	2058	77	5864	7053	27	4147	4116
28	8236	2142	78	5824	7171	28	4118	4284
29	8179	2226	79	5783	7291	29	4090	4453
0.30	8123	2311	0.80	5743	7411	1.30	4061	4623
31	8066	2397	81	5704	7532	31	4033	4794
32	8011	2483	82	5664	7654	32	4005	4967
33	7955	2570	83	5625	7777	33	3978	5140
34	7900	2658	84	5586	7901	34	3950	5315
35	7846	2746	85	5548	8025	35	3923	5491
36	7792	2834	86	5510	8150	36	3896	5669
37	7738	2924	87	5471	8276	37	3869	5847
38	7684	3014	88	5434	8404	38	3842	6027
39	7631	3104	89	5396	8532	39	3816	6208
0.40	7579	3195	0.90	5359	8661	1.40	3789	6390
41	7526	3287	91	5322	8790	41	3763	6574
42	7474	3379	92	5285	8921	42	3729	6759
43	7423	3472	93	5249	9053	43	3711	6945
44	7371	3566	94	5212	9185	44	3686	7132
45	7321	3660	95	5176	9319	45	3660	7321
46	7270	3755	96	5141	9453	46	3635	7511
47	7220	3851	97	5105	9588	47	3610	7702
48	7170	3948	98	5070	9725	48	3585	7895
49	7120	4044	99	5035	9862	49	3560	8089

ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.
1.50	0.3536	2.8284	2.00	0.2500	4.0000	2.50	0.1768	5.6569
51	3511	8481	01	2483	0278	51	1756	6962
52	3487	8679	02	2466	0558	52	1743	7358
53	3463	8879	03	2449	0840	53	1731	7757
54	3439	9079	04	2432	1125	54	1719	8159
55	3415	9282	05	2415	1411	55	1708	8563
56	3392	9485	06	2398	1699	56	1696	8971
57	3368	9690	07	2382	1989	57	1684	9381
58	3345	9897	08	2365	2281	58	1672	9794
59	3322	3.0105	09	2349	2575	59	1661	6.0210
1.60	3299	0314	2.10	2333	2871	2.60	1649	0629
61	3276	0525	11	2316	3169	61	1638	1050
62	3253	0737	12	2300	3469	62	1627	1475
63	3231	0951	13	2285	3772	63	1615	1903
64	3209	1166	14	2269	4076	64	1604	2333
65	3186	1383	15	2253	4383	65	1593	2767
66	3164	1602	16	2238	4691	66	1582	3203
67	3143	1821	17	2222	5002	67	1571	3643
68	3121	2043	18	2207	5315	68	1560	4086
69	3099	2266	19	2192	5631	69	1550	4532
1.70	3078	2490	2.20	2176	5948	2.70	1539	4980
71	3057	2716	21	2161	6268	71	1528	5432
72	3035	2944	22	2146	6589	72	1518	5887
73	3015	3173	23	2132	6913	73	1507	6346
74	2994	3404	24	2117	7240	74	1497	6807
75	2973	3636	25	2102	7568	75	1487	7272
76	2952	3870	26	2088	7899	76	1476	7740
77	2932	4105	27	2073	8232	77	1466	8211
78	2912	4343	28	2059	8568	78	1456	8685
79	2892	4581	29	2045	8906	79	1446	9163
1.80	2872	4822	2.30	2031	9246	2.80	1436	9644
81	2852	5064	31	2017	9588	81	1426	7.0128
82	2832	5308	32	2003	9933	82	1416	0616
83	2813	5554	33	1989	5.0281	83	1406	1107
84	2793	5801	34	1975	0631	84	1397	1602
85	2774	6050	35	1961	0983	85	1387	2100
86	2755	6301	36	1948	1337	86	1377	2602
87	2736	6553	37	1934	1694	87	1368	3107
88	2717	6808	38	1921	2054	88	1358	3615
89	2698	7064	39	1908	2416	89	1350	4110
1.90	2679	7321	2.40	1895	2780	2.90	1340	4643
91	2661	7581	41	1882	3147	91	1330	5162
92	2643	7842	42	1869	3517	92	1321	5685
93	2624	8106	43	1856	3889	93	1312	6211
94	2606	8371	44	1843	4264	94	1303	6741
95	2588	8637	45	1830	4642	95	1294	7275
96	2570	8906	46	1817	5022	96	1285	7812
97	2553	9177	47	1805	5404	97	1276	8354
98	2535	9449	48	1792	5790	98	1267	8899
99	2517	9724	49	1780	6178	99	1259	9447

ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi$ mm.
3.00	0.1250	8.0000	3.50	0.0884	11.314	4.00	0.0625	16.000
01	1241	0556	51	0878	392	01	0621	111
02	1233	1117	52	0872	472	02	0616	223
03	1224	1681	53	0866	551	03	0612	336
04	1216	2249	54	0860	632	04	0608	450
05	1207	2821	55	0854	713	05	0604	564
06	1199	3397	56	0848	794	06	0600	679
07	1191	3977	57	0842	876	07	0595	795
08	1183	4561	58	0836	959	08	0591	912
09	1174	5150	59	0830	12.042	09	0587	17.030
3.10	1166	5742	3.60	0825	126	4.10	0583	148
11	1158	6338	61	0819	210	11	0579	268
12	1150	6939	62	0813	295	12	0575	388
13	1142	7544	63	0808	381	13	0571	509
14	1134	8152	64	0802	467	14	0567	630
15	1127	8766	65	0797	553	15	0563	753
16	1119	9383	66	0791	641	16	0559	877
17	1111	9.0005	67	0786	729	17	0556	18.001
18	1103	0631	68	0780	817	18	0552	126
19	1096	1261	69	0775	906	19	0548	252
3.20	1088	1896	3.70	0769	996	4.20	0544	379
21	1081	2535	71	0764	13.086	21	0540	507
22	1073	3179	72	0759	178	22	0537	635
23	1066	3827	73	0754	269	23	0533	765
24	1058	4479	74	0748	361	24	0529	896
25	1051	5137	75	0743	454	25	0526	19.027
26	1044	5798	76	0738	548	26	0522	160
27	1037	6465	77	0733	642	27	0518	293
28	1029	7136	78	0728	737	28	0515	427
29	1022	7811	79	0723	833	29	0511	562
3.30	1015	8492	3.80	0718	929	4.30	0508	698
31	1008	9177	81	0713	14.026	31	0504	835
32	1001	9866	82	0708	123	32	0501	973
33	0994	10.0561	83	0703	221	33	0497	20.112
34	0988	1261	84	0698	320	34	0494	252
35	0981	1965	85	0693	420	35	0490	393
36	0974	2674	86	0689	520	36	0487	535
37	0967	3388	87	0684	621	37	0484	678
38	0960	4107	88	0679	723	38	0480	821
39	0954	4831	89	0675	825	39	0477	966
3.40	0947	5561	3.90	0670	929	4.40	0474	21.112
41	0941	6295	91	0665	15.032	41	0470	259
42	0934	7034	92	0661	137	42	0467	407
43	0928	7779	93	0656	242	43	0464	556
44	0921	8528	94	0652	348	44	0461	706
45	0915	9283	95	0647	455	45	0458	857
46	0909	11.0043	96	0643	562	46	0454	22.009
47	0902	0809	97	0638	671	47	0451	162
48	0896	1579	98	0634	780	48	0448	316
49	0890	2356	99	0629	889	49	0445	471

ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.
4.50	0.0442	22.627	5.00	0.0313	32.000	5.50	0.0221	45.255
51	0439	785	01	0310	223	51	0219	570
52	0436	943	02	0308	447	52	0218	886
53	0433	23.103	03	0306	672	53	0216	46.206
54	0430	264	04	0304	900	54	0215	527
55	0427	425	05	0302	33.128	55	0213	851
56	0424	588	06	0300	359	56	0212	47.177
57	0421	752	07	0298	591	57	0211	505
58	0418	918	08	0296	825	58	0209	835
59	0415	24.084	09	0294	34.060	59	0208	48.168
4.60	0412	251	5.10	0292	297	5.60	0206	503
61	0409	420	11	0290	535	61	0205	840
62	0407	590	12	0288	776	62	0203	49.180
63	0404	761	13	0286	35.017	63	0202	522
64	0401	933	14	0284	261	64	0201	867
65	0398	25.107	15	0282	506	65	0199	50.213
66	0396	281	16	0280	753	66	0198	563
67	0393	457	17	0278	36.002	67	0196	914
68	0390	634	18	0276	252	68	0195	51.268
69	0387	813	19	0274	504	69	0194	625
4.70	0385	992	5.20	0272	758	5.70	0192	984
71	0382	26.173	21	0270	37.014	71	0191	52.346
72	0379	355	22	0268	271	72	0190	710
73	0377	538	23	0266	531	73	0188	53.076
74	0374	723	24	0265	792	74	0187	446
75	0372	909	25	0263	38.055	75	0186	817
76	0369	27.096	26	0261	319	76	0185	54.192
77	0367	284	27	0259	586	77	0183	569
78	0364	474	28	0257	854	78	0182	948
79	0361	665	29	0256	39.124	79	0181	55.330
4.80	0359	858	5.30	0254	397	5.80	0179	715
81	0356	28.051	31	0252	671	81	0178	56.103
82	0354	246	32	0250	947	82	0177	493
83	0352	443	33	0249	40.224	83	0176	886
84	0349	641	34	0247	504	84	0175	57.282
85	0347	840	35	0245	786	85	0173	680
86	0344	29.041	36	0243	41.070	86	0172	58.081
87	0342	243	37	0242	355	87	0171	485
88	0340	446	38	0240	643	88	0170	892
89	0337	651	39	0238	933	89	0169	59.302
4.90	0335	857	5.40	0237	42.224	5.90	0167	714
91	0333	30.065	41	0235	518	91	0166	60.129
92	0330	274	42	0234	814	92	0165	548
93	0328	484	43	0232	43.111	93	0164	969
94	0326	696	44	0230	411	94	0163	61.393
95	0324	910	45	0229	713	95	0162	820
96	0321	31.125	46	0227	44.017	96	0161	62.250
97	0319	341	47	0226	426	97	0160	683
98	0317	559	48	0224	632	98	0158	63.119
99	0315	779	49	0223	942	99	0157	558

ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	$(-\phi)$ mm.	ϕ	$(+\phi)$ mm.	ϕ	$(+\phi)$ mm.
6.00	0.0156	64.000	6.50	0.0110	90.510	7.00	0.0078	7.50	0.0055
01	0155	445	51	0110	91.139	01	0078	51	0055
02	0154	893	52	0109	773	02	0077	52	0055
03	0153	65.345	53	0108	92.411	03	0077	53	0054
04	0152	799	54	0107	93.054	04	0076	54	0054
05	0151	66.257	55	0107	701	05	0076	55	0053
06	0150	718	56	0106	94.353	06	0075	56	0053
07	0149	67.182	57	0105	95.010	07	0074	57	0053
08	0148	649	58	0105	670	08	0074	58	0052
09	0147	68.120	59	0104	96.336	09	0073	59	0052
6.10	0146	594	6.60	0103	97.006	7.10	0073	7.60	0052
11	0145	69.071	61	0102	681	11	0072	61	0051
12	0144	551	62	0102	98.360	12	0072	62	0051
13	0143	70.035	63	0101	99.044	13	0071	63	0051
14	0142	522	64	0100	733	14	0071	64	0050
15	0141	71.012	65	0100	100.427	15	0070	65	0050
16	0140	506	66	0099		16	0070	66	0049
17	0139	72.004	67	0098		17	0069	67	0049
18	0138	505	68	0098		18	0069	68	0049
19	0137	73.009	69	0097		19	0069	69	0048
6.20	0136	517	6.70	0096		7.20	0068	7.70	0048
21	0135	74.028	71	0096		21	0068	71	0048
22	0134	543	72	0095		22	0067	72	0047
23	0133	75.061	73	0094		23	0067	73	0047
24	0132	584	74	0094		24	0066	74	0047
25	0131	76.109	75	0093		25	0066	75	0047
26	0130	639	76	0092		26	0065	76	0046
27	0130	77.172	77	0092		27	0065	77	0046
28	0129	708	78	0091		28	0064	78	0046
29	0128	78.249	79	0090		29	0064	79	0045
6.30	0127	793	6.80	0090		7.30	0064	7.80	0045
31	0126	79.341	81	0089		31	0063	81	0045
32	0125	893	82	0089		32	0063	82	0044
33	0124	80.449	83	0088		33	0062	83	0044
34	0123	81.008	84	0087		34	0062	84	0044
35	0123	572	85	0087		35	0061	85	0043
36	0122	82.139	86	0086		36	0061	86	0043
37	0121	711	87	0086		37	0061	87	0043
38	0120	83.286	88	0085		38	0060	88	0043
39	0119	865	89	0084		39	0060	89	0042
6.40	0118	84.449	6.90	0084		7.40	0059	7.90	0042
41	0118	85.036	91	0083		41	0059	91	0042
42	0117	627	92	0083		42	0058	92	0041
43	0116	86.223	93	0082		43	0058	93	0041
44	0115	823	94	0081		44	0058	94	0041
45	0114	87.427	95	0081		45	0057	95	0040
46	0114	88.035	96	0080		46	0057	96	0040
47	0113	647	97	0080		47	0056	97	0040
48	0112	89.264	98	0079		48	0056	98	0040
49	0111	884	99	0079		49	0056	99	0039

ϕ	$(+\phi)$ mm.	ϕ	$(+\phi)$ mm.	ϕ	$(+\phi)$ mm.	ϕ	$(+\phi)$ mm.
8.00	0.0039	8.50	0.0028	9.00	0.0020	9.50	0.0014
01	0039	51	0027	01	0019	51	0014
02	0039	52	0027	02	0019	52	0014
03	0038	53	0027	03	0019	53	0014
04	0038	54	0027	04	0019	54	0013
05	0038	55	0027	05	0019	55	0013
06	0038	56	0027	06	0019	56	0013
07	0037	57	0026	07	0019	57	0013
08	0037	58	0026	08	0019	58	0013
09	0037	59	0026	09	0018	59	0013
8.10	0036	8.60	0026	9.10	0018	9.60	0013
11	0036	61	0026	11	0018	61	0013
12	0036	62	0025	12	0018	62	0013
13	0036	63	0025	13	0018	63	0013
14	0035	64	0025	14	0018	64	0013
15	0035	65	0025	15	0018	65	0012
16	0035	66	0025	16	0018	66	0012
17	0035	67	0025	17	0017	67	0012
18	0035	68	0024	18	0017	68	0012
19	0034	69	0024	19	0017	69	0012
8.20	0034	8.70	0024	9.20	0017	9.70	0012
21	0034	71	0024	21	0017	71	0012
22	0034	72	0024	22	0017	72	0012
23	0033	73	0024	23	0017	73	0012
24	0033	74	0023	24	0017	74	0012
25	0033	75	0023	25	0016	75	0012
26	0033	76	0023	26	0016	76	0012
27	0032	77	0023	27	0016	77	0012
28	0032	78	0023	28	0016	78	0011
29	0032	79	0023	29	0016	79	0011
8.30	0032	8.80	0022	9.30	0016	9.80	0011
31	0032	81	0022	31	0016	81	0011
32	0031	82	0022	32	0016	82	0011
33	0031	83	0022	33	0016	83	0011
34	0031	84	0022	34	0015	84	0011
35	0031	85	0022	35	0015	85	0011
36	0030	86	0022	36	0015	86	0011
37	0030	87	0021	37	0015	87	0011
38	0030	88	0021	38	0015	88	0011
39	0030	89	0021	39	0015	89	0011
8.40	0030	8.90	0021	9.40	0015	9.90	0011
41	0029	91	0021	41	0015	91	0010
42	0029	92	0021	42	0015	92	0010
43	0029	93	0021	43	0015	93	0010
44	0029	94	0020	44	0014	94	0010
45	0029	95	0020	45	0014	95	0010
46	0028	96	0020	46	0014	96	0010
47	0028	97	0020	47	0014	97	0010
48	0028	98	0020	48	0014	98	00099
49	0028	99	0020	49	0014	99	00098
						10.00	00098

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 293–296
FIGS. 1–2, DECEMBER, 1955

A THEORETICAL CURVE FOR STATISTICAL ANALYSIS OF SEDIMENTS

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ABSTRACT

The cumulative frequency-curve is a valuable and commonly used statistical curve, but is difficult to interpret except comparatively. To facilitate interpretation of an empirical cumulative curve, a theoretical curve of perfect grade-size distribution can be superimposed by: (a) drawing on logarithmic probability paper a straight line between points representing the maximum and minimum grade sizes of the sample, (b) transferring this line to the semi-logarithmic paper upon which the empirical data are also plotted.

The cumulative frequency-curve, or ogive, with the general formula $\int_{-\infty}^{x} e^{-kx^2}(dx)$ is probably the most commonly used two-variable curve-graph in sedimentary work. The other basic line- and curve-graphs are the histogram, frequency-polygon, and simple frequency-curve with the general formula $y = e^{-kx^2}$. All of these are related mathematically. The histogram and frequency-polygon represent a discrete frequency distribution (i.e., show only limited gradations without fractions of a grade scale) whereas the simple and the cumulative frequency-curves represent a continuous distribution (i.e., every size gradation is shown between the given limits). Thus, the simple and cumulative curves represent a continuous series and their shape is not affected by the grade scale used.

The cumulative frequency-curve also has the valuable characteristic of yielding directly a quantity of statistical parameters. All of the quartiles, deciles, and percentiles can be obtained by visual inspection of the curve, and the quartile measures commonly used (the median, deviation, skewness, and kurtosis) are likewise obtained or readily computed. Several of the moment measures are indicated also, although moment parameters generally are better illustrated with the simple frequency-curve $y = e^{-kx^2}$.

Cumulative curves have, however, some disadvantages. When used to show the characteristics of a single sample, the coordinate data are clear but the cumulative curve itself is fundamentally difficult to interpret except comparatively. When used to compare graphically a quantity of samples, the curves normally are superimposed so that direct visual comparison is possible. Since the superimposition tends to obscure the individual curves, this works satisfactorily only if there are few samples or if no exact coordinate data are desired, or if the graph is only a general presentation.

To alleviate these disadvantages a theoretical curve of perfect symmetry can be plotted over the empirical cumulative curve. This theoretical curve varies only with the maximum spread of the grade sizes; therefore, it remains constant for any region, environment, geological agent, or suite of samples for which the spread is determined. It serves

TABLE 1.—*Grade-size distribution of a common beach sand (Krumbein and Sloss, 1951), which is used in preparation of the sample curves in figs. 1 and 2; (A) and (B) are maximum and minimum grade sizes respectively.*

(A) 2–1 mm.—1%	$\frac{1}{2}$–$\frac{1}{4}$ mm.—34%	(B) $\frac{1}{8}$–$\frac{1}{16}$ mm.—1%
1–$\frac{1}{2}$ mm.—6%	$\frac{1}{4}$–$\frac{1}{8}$ mm.—58%	

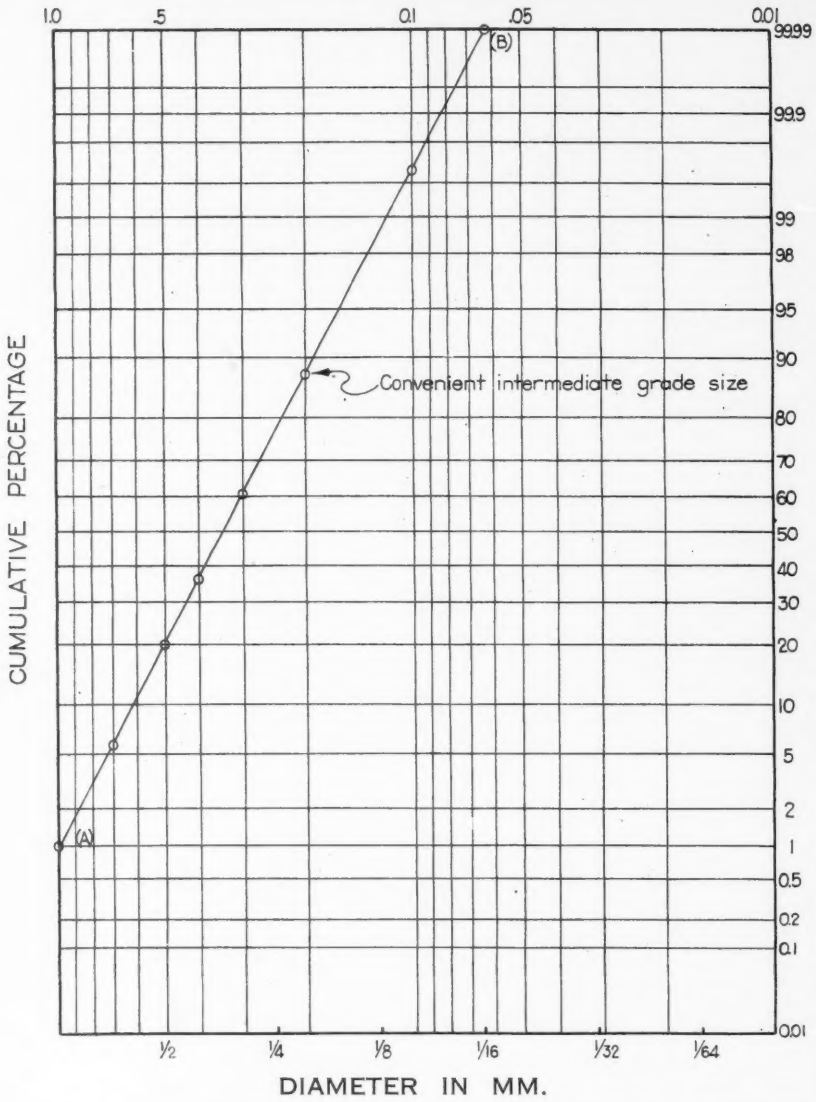

FIG. 1.—First Step: Locate points (A) and (B) on probability paper; connect these points with a straight line; select from that line convenient intermediate points which can be transferred easily to semi-log paper.

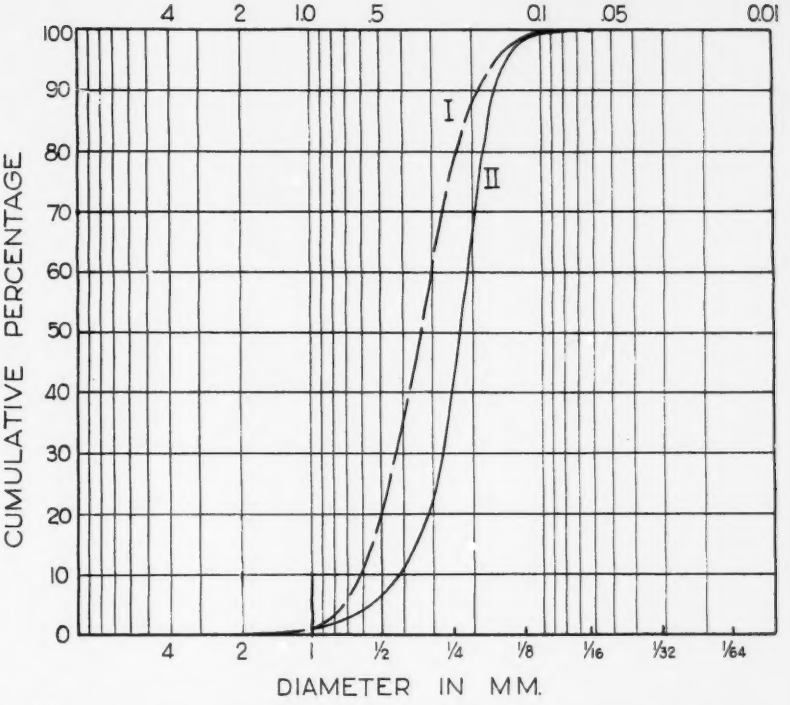

FIG. 2.—Second Step: draw a smooth curve through the points transferred from probability paper. Curve I is this theoretical cumulative curve of perfect grade-size distribution, whereas Curve II is the empirical curve of actual distribution. Comparison of the two readily shows the characteristic deviation of this beach sand.

as a statistical standard to which each empirical curve can be compared and through which each can be compared to every other without the necessity of graphically superimposing them.

The theoretical curve is easily obtained. Since data forming a symmetrical cumulative frequency-curve will also plot as a straight line on probability paper (Krumbein and Pettijohn, 1938), it is necessary only to draw the straight line first, proceeding as follows:

(1) Draw on logarithmic probability paper a straight line between the average maximum and minimum grade sizes of the suite of samples, using, for practical purposes, the 99.99 cumulative percentage line for 100 cumulative percent of the sample (table 1 and fig. 1).

(2) Graphically interpolate the percentages of a sufficient number of any convenient intermediate grade sizes (fig. 1).

(3) Transfer these corresponding percentages and sizes to the semi-logarithmic paper upon which the cumulative data are plotted.

(4) Plot through these new points the new curve (fig. 2, curve 1). Once drawn for a given spread of grade sizes, the

theoretical curve can be traced onto each worksheet.

The writer has applied this technique to hundreds of samples during the last few years and found it to be a good analytical tool as well as a convenient mnemonic.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 297–301
DECEMBER, 1955

STUDENT OPERATOR ERROR IN DETERMINATION OF ROUNDNESS, SPHERICITY, AND GRAIN SIZE

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ABSTRACT

Operator error in the use of Powers roundness images has been studied. A logarithmic scale is proposed for the statistical analysis of roundness counts and determination of mean roundness and roundness standard deviation. Experimental error in determination of mean roundness from counts of fifty grains was ± 0.35 roundness class, a relatively large value considering the small range of mean roundness encountered. Pebble sphericities were determined by the three-diameter method; operator error here was virtually negligible, amounting to only ± 0.02 in a range of values from 0.41 to 0.85. Error in determination of phi median size and phi standard deviation by sieving were likewise exceedingly small, amounting to only $\pm 0.02\phi$ in median diameter. This surprisingly small value for operator error is ascribed to the use of probability paper, as variation in determination of parameters was much greater when ordinary squared paper was used.

INTRODUCTION

The recent trend toward quantification of data in sedimentary petrology has lead to consideration of how much the differences observed are due to experimental error. Recent work on this subject has been done by Griffiths and Rosenfeld (1954), who have presented an excellent review of their own findings and the results of others in the field.

During the past several semesters the writer has conducted a series of tests with senior and graduate students at the University of Texas in an attempt to study operator error in the following experiments: (1) determination of sand grain roundness using the Powers Roundness comparison images; (2) determination of pebble sphericites by the three-diameter method; and (3) determination of median size and sorting of sands by hand-sieving. Experimental error has been found to be surprisingly small in sphericity and grain size values but quite large in roundness estimations.

OPERATOR ERROR IN ROUNDNESS

For roundness determinations of sand grains, the writer has found the roundness images of Powers (1953) vastly superior to earlier methods. Powers' adaptation of logarithmic class intervals is a marked forward step in this field. When log roundness is plotted against cumulative percent of grains on probability paper, analyses plot out very nearly as straight lines indicating that the distribution is lognormal. As in any logarithmic scale, though, the mathematics becomes somewhat difficult. Just as Krumbein (1934) developed the phi scale to aid mathematical analysis of logarithmic grain size intervals, so a "rho" scale can be formulated for the logarithmic roundness intervals in order to simplify computations. The following scale was adopted as being most suitable, since each roundness class has a different integer (considerably facilitating memory) and the numerical values cover a wide range.

Powers Verbal Class	Corresponding Wadell Class Intervals	Rho Scale Class Intervals
Very Angular	.12– .17	0.00–1.00
Angular	.17– .25	1.00–2.00
Subangular	.25– .35	2.00–3.00
Subrounded	.35– .49	3.00–4.00
Rounded	.49– .70	4.00–5.00
Well-rounded	.70–1.00	5.00–6.00

Results of roundness counts are plotted as cumulative curves on *arithmetic probability* paper, plotting the percentage of very angular grains at an abscissa of 1.00, very angular plus angular at 2.00 etc. Median (or mean) roundness, standard deviation of roundness, roundness skewness, and roundness kurtosis can then be determined by the standard intercept techniques of cumulative curve analysis familar to grain-size workers.

In the experiment, four sand samples were picked to show wide range in mean roundness, varying from Escatawpa River sand, Mississippi, to dune sand from Crane County, Texas. Each sample was sieved into 1–2ϕ size grades and 2–3ϕ size grades and the grains were placed in vials. Each operator was assigned to count 50 grains in both size grades of two sand samples; a spray of grains was poured from the vial on a gridded black background and counted with a binocular microscope using the Powers images. Consequently each man counts different grains although all are from the same vial. Sixteen different operators worked on each of eight vials (four samples times two size grades), and determined mean roundness by the formula

$$M_\rho = \frac{\rho 16 + \rho 50 + \rho 84}{3}$$

and standard deviation of roundness by the formula

$$\sigma_\rho = \frac{\rho 84 - \rho 16}{2}$$

where $\rho 16$ equals the roundness value at the 16 percent mark, etc. To determine experimental error, the standard deviation of the sixteen mean roundness values obtained by the different operators was computed for each vial. The variances (σ^2) were then summed for all eight vials, and the total divided by eight to get the mean variance. Mean standard deviation (the square root of the mean variance) was ± 0.35 roundness class. This total experimental error of ± 0.35 is due to (1) subsample error, in that each operator counted a different suite of grains from the same vial, and (2) operator error, i.e. a grain that looks subround to one operator may look subangular to another one. These two components of the total error were not separately evaluated because the experiment was designed to duplicate routine laboratory conditions where time for complete replication of analyses is not available. This figure shows that if one takes a sample whose true mean roundness is 2.50 (subangular) and gives it to 100 different operators who each count 50 grains, 68 of them will obtain mean roundness between 2.15 and 2.85 and all but five will be within the range of 1.80 to 3.20. This experimental variation is quite large considering that mean roundness for the eight vials (obtained by averaging the mean roundness obtained by all sixteen operators for that vial) varied from 2.26 (2–3ϕ grade of Escatawap River sand) to 3.43 (1–2ϕ grade of Crane County aeolian sand).

ROUNDNESS STANDARD DEVIATION

In addition to determining operator error we may also compute the standard deviation of roundness for each sample—i.e. roundness sorting. In the samples analyzed above, σ_ρ ranged from 0.82 for Crane County aeolian sand in which nearly all the grains were subround, to 1.22 for Colorado River sand, which contains a mixture of angular grains eroded directly from central Texas igneous and metamorphic rocks together with well-rounded grains derived from Cambrian supermature orthoquartzite sandstones; this sand also has a skewed roundness distribution in contrast to the other samples which all plotted as nearly straight lines on probability paper. In other samples which the writer has analyzed, σ_ρ has ranged between 0.6 and 1.4. Plots of mean roundness against standard deviation of roundness may offer fruitful clues to environments. Unfortunately the large values so far encountered for roundness standard deviation indicate that a con-

siderable number of sand grains must be counted to distinguish statistically between samples. For example (applying the t test, assuming an average σ_ρ of 1.00, and rejecting as not significant all values of P above .05), if 100 grains of each of two samples are counted, then the difference between their means must be greater than .28 to be considered significant; if 400 grains of each sample are counted, then a difference of as little as .14 roundness grade becomes significant. The writer will welcome other worker's results on roundness standard deviation, so that we may begin to get some idea on the limits of "good" roundness sorting, "poor" roundness sorting, etc. Samples analyzed so far indicate the following limits: σ_ρ under 0.70, very good roundness sorting; σ_ρ 0.70–0.90, good roundness sorting; σ_ρ 1.10–1.30, poor roundness sorting; and σ_ρ over 1.30, very poor roundness sorting.

OPERATOR ERROR IN SPHERICITY DETERMINATIONS

A suite of some 75 pebbles ranging from 32 to 64 mm in long dimension was collected from Colorado River gravels at Austin, for evaluation of operator error in measurements of sphericity. Each operator took a caliper and measured what he thought to be the three axes of the pebble, chosen at right angles to each other. No guidance was furnished by the writer, and each man was "on his own" in picking the diameters. None of them had ever measured a pebble before. Under such conditions it might be thought that there would be a very large operator error in sphericity measurements, especially in choice of the diameters; however, the results were startlingly close. The sphericity measure used was the Effective Settling sphericity,

$$\sqrt[3]{\frac{S^2}{LI}}$$

where S, L, and I stand for short, long, and intermediate diameters respectively. This measure is defined as the value obtained by dividing the maximum projection area of a pebble (L×I) into the maximum projection area of a sphere of the same volume. This gives a more realistic value of sphericity than the customary Wadell (1932) measure because particles tend to settle with their maximum projection area lying horizontal, and this becomes the effective surface area resisting downward motion; the new measure will be discussed in a forthcoming paper by the writer and Edmund Sneed. Values of effective settling sphericity so far obtained range from 0.3 (low sphericity) to 0.9, approximately the range of the Wadell sphericities, so that operator error evaluated here also applies approximately to that computed by the more usual Wadell formula. Again the same procedure was used for computing experimental error: each pebble was measured by six operators, and each operator determined sphericity by the above formula. Then for each pebble the standard deviation of the six sphericity values was obtained. The experimetal error averaged out to only ± 0.021 in a range of values for these pebbles between 0.41 and 0.85 —e.g. if a pebble with sphericity of 0.75 was handed to 100 different operators to measure, 68 of them would obtain values between 0.73 and 0.77, and only five would obtain values outside of the range 0.71–0.79. Since different pebbles from any area show a range in sphericity much wider than this, experimental error is negligible in sphericity measurement.

OPERATOR ERROR IN GRAIN SIZE ANALYSIS

Thirty-two sand samples varying in median from 0.70ϕ to 3.40ϕ and in sorting (in terms of the σ_ϕ of Otto, 1939) from 0.25 to 1.40, were split into two subsamples by an Otto microsplit and assigned to two different operators to sieve. Because of large classes it is not possible for students to use a Ro-Tap and standard eight inch screens spaced at $\frac{1}{4}\phi$ in-

tervals; instead they must do their sieving by hand using three inch diameter screens spaced at 1ϕ intervals. Each operator took his split (weighing between 10 and 20 grams), disaggregated it to crush mud lumps and salt-bonded grains, and sieved for 10 minutes using a rotary motion and jarring the sieves against a table every few seconds. Sieve fractions were then weighed on a triple beam balance of 0.01 gram, percentages computed, and cumulative curves plotted using the phi scale and arithmetic probability paper. Medians and sorting coefficients (σ_ϕ) were computed by reading diameter intercepts at the 16, 50, and 84 percentiles. It is to be emphasized that all operators were completely inexperienced both as to the techniques of sieving and the method of plotting. The experimental error in determination of the median was found to be only $\pm.02\phi$ in terms of standard deviation—in other words if a sample with a median of 2.50ϕ is given to 100 operators to sieve under these conditions, 68 of them will obtain medians between 2.48ϕ and 2.52ϕ and only five will obtain medians outside the range of 2.46ϕ to 2.54ϕ. This is remarkably close especially under these conditions, where the total experimental error consists of all the following components: (1) splitting error—i.e. the sample splitter may not divide the original sample into subsamples of equal grain size; (2) variation in effectiveness of disaggregation between operators; (3) variation in effectiveness of hand sieving motion between operators; (4) variations in weighing using small samples and rather crude scales; and (5) error in plotting curves and in interpolating between such widely spaced size intervals. In evaluating these five sources of error it was found that by far the largest source of error was in curve drawing—actual analysis points often coincided between operators, but the shape of the interpolated curve between the points varied considerably. The writer was frankly surprised at such small experimental error, and attributes the closeness of the results to the use of probability paper. Students also plotted these results on ordinary squared paper and the variation in median here was very marked because of the lesser certainty of extrapolation. Because of this experience the writer now uses probability paper exclusively; the use of ordinary squared paper is considered as worse than useless and may account for some of the poor grain size results obtained in the past.

The students also obtained sorting values in terms of standard deviations for each sample; the experimental error here was also very slight, amounting to only ± 0.027 in a range of σ_ϕ from 0.25 to 1.40.

CONCLUSIONS

Experimental error in determination of sphericity of individual pebbles is negligible, averaging only ± 0.02 in a range of values from .41 to .85. Error is similarly slight in determinations of medians and standard deviation of grain size distributions, averaging only $\pm 0.02\phi$ for the median diameter in a range of values from 0.70ϕ to 3.40ϕ and only ± 0.03 for sorting coefficient, σ_ϕ, in a range of values from 0.25 to 1.40. The use of probability paper is regarded as contributing greatly to the minimization of error in this experiment. Experimental error in determination of roundness is quite large, averaging ± 0.35 roundness grade in a range of values from about 2.2 to 3.4; consequently a large number of grains must be counted to establish significant roundness differences between samples, and great precaution must be taken to insure against operator bias.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 302–303
FIGS. 1–2, DECEMBER, 1955

MOUNTING TECHNIQUE FOR GRAIN SIZE AND SHAPE MEASUREMENT

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ABSTRACT

A new technique for mounting sand grains was developed during a recent size and shape analysis conducted by the author. Grains are sampled using an Otto microsplit and are imbedded in Castolite thermosetting plastic. Mounts are made in the shape of a rectangular rod which makes it easy to view the grains at right angles and makes them readily stowable.

A large number of techniques exist for the measurment of grain size and shape (Krumbein and Pettijohn, 1938), but it is of considerable advantage to be able to measure size and shape on the same grain (*Griffiths, 1952*). In order to achieve this desirable objective it is necessary to examine both the maximum and minimum projection areas of the grain, and this entails turning the grain through 90 degrees. Measurement of grain size in loose grains has been described by Pye (*1943*) and Plumley proposed a mounting technique which permits three dimensional measurement of sand grains (1948).

A sample of loose grains is obtained either by brushing the rock as described by Pye (1943) or, if necessary, by more elaborate disaggregation procedures. Fifty grains appear ample for our purpose, and as quartz is the only mineral of interest, destruction of other materials in the rock presents no problem and simplifies considerably the reduction of the rocks to the component grains. The sample is then passed through an Otto microsplit (1933) until the necessary 50 grains remain. These fifty grains are spread out in a single line on a sheet of paper ready for mounting.

The mounting medium is Castolite,[1] a thermo-setting plastic, and to enable the grains to be turned through 90°, the shape of the mount is a rectangular rod with square ends. The shape is obtained by means of a mold made of polished aluminum (fig. 1). Specifically the procedure is as follows:

The mold is coated with a releasing compound—glycerin is recommended by Castolite—and is then assembled. The plastic is prepared in a watch glass in two batches; two or three drops of Castolite liquid hardener are added and thoroughly mixed with enough plastic to half fill the mold. This is followed by one to two drops of Castolite cold setting promoter and again mixed. The mixed plastic is now transferred to the mold and allowed to set for five minutes at room temperature. The additives hasten the jelling of the plastic.

At this stage the plastic is in suitable condition for mounting the grains; they

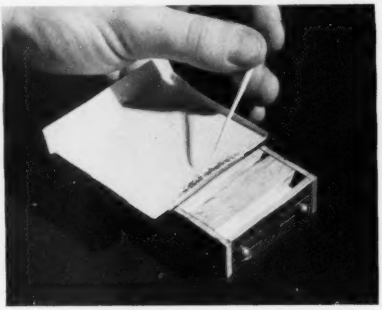

FIG. 1.—Mounting grains in aluminum mold on first batch of plastic.

[1] Castolite products may be purchased through Ward's Natural Science Establishment, Inc., Rochester, New York; the mold was made in the machine shop at the College of Mineral Industries at the Pennsylvania State University.

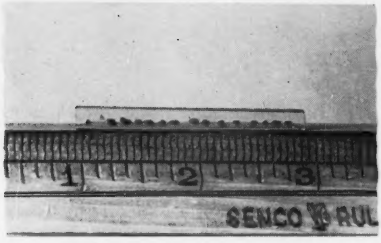

FIG. 2.—Completed plastic rod with grains from Pottsville quartzite, Central Pennsylvania.

are transferred from the sheet of paper to the plastic and lined up along the rod. There is a thin liquid layer of plastic at the surface or, if the plastic has hardened, the grains may be mounted in a layer of water above the plastic. It is very necessary at this stage to ensure that the grains have every opportunity to achieve their stable position and therefore expose their maximum projection areas. When the grains are mounted satisfactorily a second batch of plastic is mixed, using half the amount of promoter, and the grains covered with a layer of plastic. The mold is then placed in an oven and the plastic cured at about 100–110° centigrade. Larger blocks of plastic demand slower curing; 15 to 25 minutes is sufficient for rods of the size used in the mold figured, and the mold is then broken down and the rod removed (fig. 2.)

Frequently it is necessary to polish the rod in order to increase the ease of light transmission. The measurements are performed under a microprojector and the grains may be numbered for individual recognition. The rectangular shape of the rod allows the examination of maximum and minimum projection areas as long as the mounting of grains is successful. One or two grains out of every 50 generally fail to achieve their proper position. It is advisable to mount more grains than will be needed for measurement and then one may random sample the mounted set.

One disadvantage in the use of castolite is that the refractive indices of quartz and castolite are so similar that definition of the edge of the grain is sometimes difficult. To some extent this lack of definition arises from the tapering edges of quartz grains so that some ambiguity will always be present. This ambiguity may be evaluated and to some extent removed by using several operators on the same grains and removing the effect of operator variation by suitable experimental design (Griffiths and Rosenfeld, 1954).

The advantages of this technique are that it supplies a direct measurement of size and shape simultaneously and results in a permanent mount which is easily stored; furthermore, by adjusting mold size, a very wide range of particles including silt to pebble size may be treated by similar technique.

This procedure was developed at the request of J. C. Griffiths, Professor of Petrography, The Pennsylvania State University, as part of a research program designed to investigate the size and shape of quartz grains in sediments.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, PP. 304–305
FIG. 1, DECEMBER, 1955

DISCUSSION

TERMINOLOGY OF LIMESTONE AND RELATED ROCKS: AN INTERIM REPORT

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The report presented by Rodgers (1954) provides an interesting and useful summary of the current state of agreement on terminology. This discussion calls attention to an attempt to present a diagrammatic outline of a system of terminology based on composition, generally in accordance with currently agreed usage in sedimentary petrology, for the guidance of engineers, petrographers, and others concerned with the use of these materials in construction. The diagrams here presented (fig. 1) are based primarily on the discussions given by Pettijohn (1949). They were first developed in response to a need for such information expressed by Subcommittee II-f on "Aggregate Mineralogical Characteristics as Related to Concrete" of Committee C-9 on Concrete and Concrete Aggregates of the American Society for Testing Materials. They formed part of the basis upon which the "Tentative Descriptive Nomenclature of Constituents of Natural Mineral Aggregates" (ASTM Designation: C 294–54T) was prepared.

The diagrams were then incorporated in a discussion (Mather, 1953) presented to the Industrial Minerals Division of the AIME and published in *Mining Engineering*. It is certainly not desired to imply that these terms nor the compositions that they are shown to designate are the final word either in terminology or in subdivision for nomenclature. It is, however, suggested that sedimentary petrologists might profitably increase their awareness of the needs of various technologies for an adequate and accurate terminology for use in their activities.

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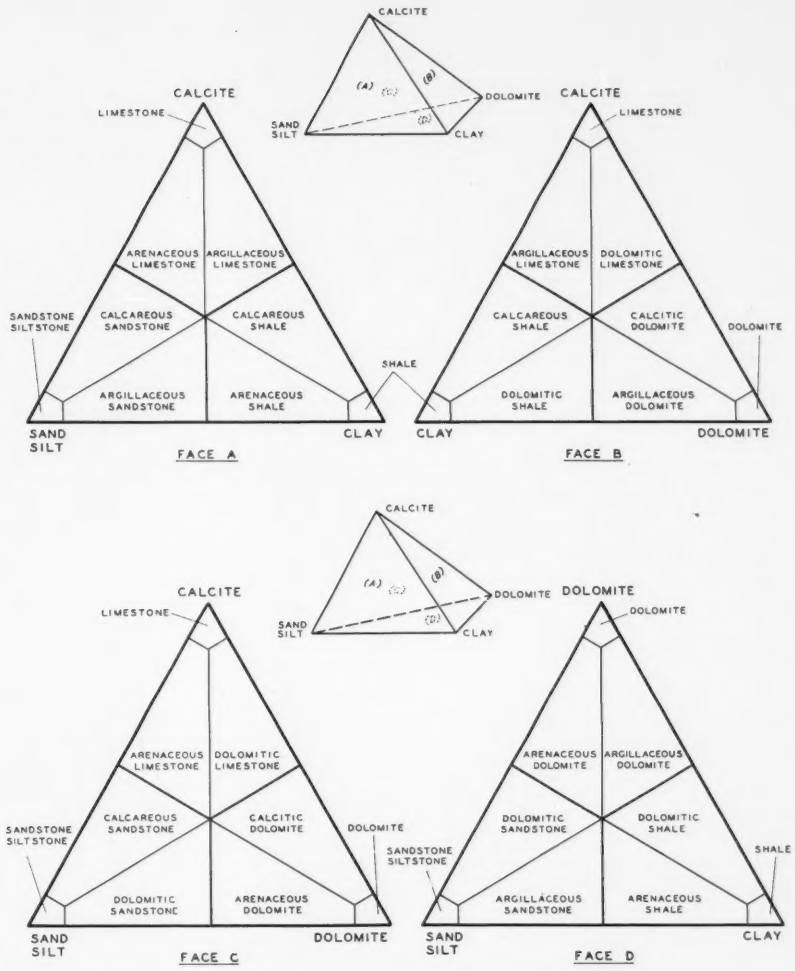

FIG. 1, A, B, C, D.—Tetrahedral diagrams showing variations in composition among rocks composed of calcite, dolomite, clay, and sand-silt.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 4, P. 306
DECEMBER, 1955

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

ANNOUNCEMENT OF PROGRAM OF 30TH ANNUAL MEETING OF SEPM, CHICAGO

APRIL, 1956

The Society of Economic Paleontologists and Mineralogists is planning a program for the Chicago 1956 meeting that will consist of the following:

1. A joint session with the A.A.P.G.
2. A single half-day session of volunteered paleontological papers with Charles Collinson, Illinois State Geological Survey, Urbana, as Chairman.
3. A single half-day session of volunteered papers on sedimentary mineralogy and petrology, sedimentology, and stratigraphy, with Lewis Cline, University of Wisconsin, Madison, as Chairman.
4. A general session, if necessary, of volunteered papers, with Lewis Cline as Chairman.
5. A symposium on "Directional Properties of Sedimentary Rocks" to be organized by the Research Committee, with Ray Siever, Illinois State Geological Survey, Urbana, as Chairman.
6. A symposium on "Paleoecology," with Harry S. Ladd, U. S. Geological Survey, Washington, and Bernhard Kummel, Harvard University, Cambridge, as Co-Chairmen.

All persons who are interested in submitting papers for the program, or who have suggestions regarding the symposia, should write directly to the respective Chairman of the particular session.

November 15 has been set as a deadline for submitting papers and abstracts for any part of the program. We earnestly solicit your cooperation in helping us to organize and carry through what we hope will be one of our outstanding programs.

ROBERT R. SHROCK
Vice President

ACKNOWLEDGEMENT

The Society of Economic Paleontologists and Mineralogists acknowledges, with thanks, the receipt of $884.28 from the New York Oil Finders Convention Committee. This gift was made possible because the following contributors to the Guarantors' Fund generously left their contribution in the convention funds.

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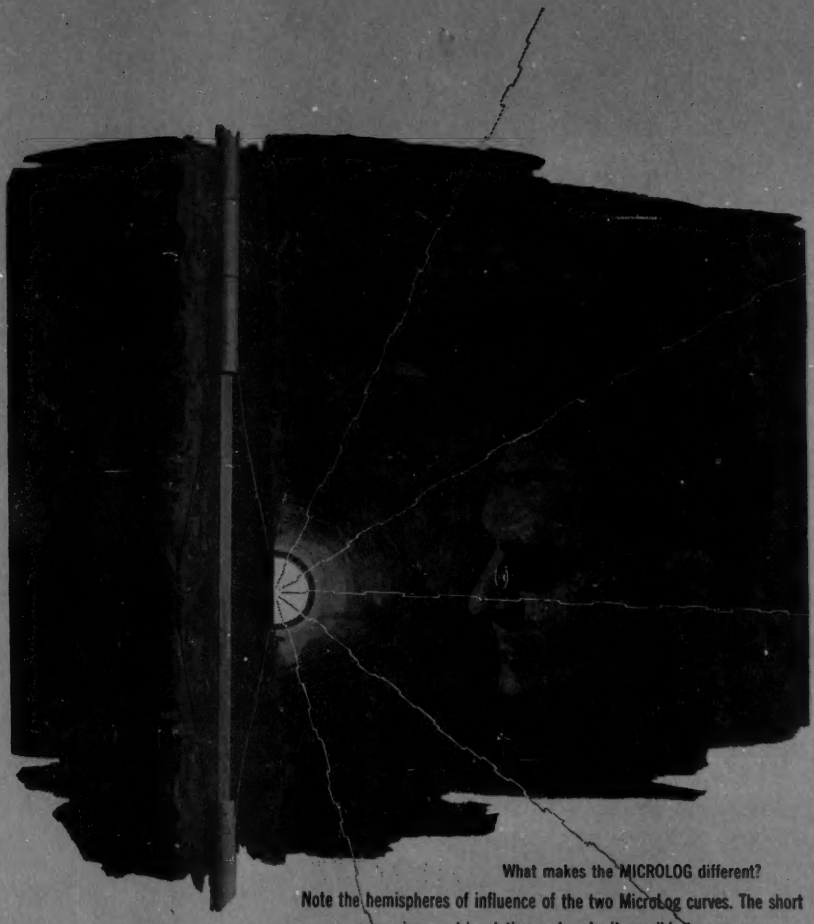

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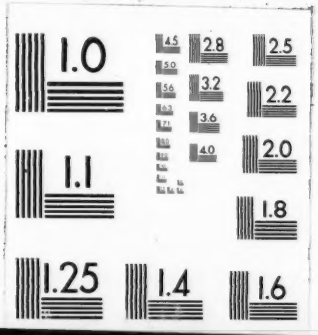
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